UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10
1200 Sixth Avenue
Seattle, WA 98101

Reply To
Attn Of: ECO-087

MEMORANDUM

SUBJECT: Columbia River Temperature Assessment: Simulation Methods

FROM: Mary Lou Soscia 2/99
Columbia River Coordinator
U.S. Environmental Protection Agency
Office of Ecosystems and Communities
811 S.W. Sixth Avenue
Portland, OR 97204

TO:

Please find attached a copy of "Columbia River Temperature Assessment: Simulation Methods." This report is currently undergoing peer review. Please provide your comments on the report by April 9 to:

John Yearsley
U. S. Environmental Protection Agency
OEA-095
1200 Sixth Avenue
Seattle, WA 98101
(206) 553-1532
Fax: 553-0119
Email: <yearsley.john@epamail.epa.gov>

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
REGION 10
1200 Sixth Avenue
Seattle, Washington 98101

COLUMBIA RIVER

TEMPERATURE ASSESSMENT:

SIMULATION METHODS

DRAFT

John Yearsley
February 1999

Columbia River Temperature Assessment
Simulation Methods
EPA Region 10

INTRODUCTION

Portions of the main stem of Columbia River from the International Border, (Columbia River Mile 745.0) to the mouth at Astoria, Oregon and the Snake River from Lewiston, Idaho (Snake River Mile 139.9) to its confluence with the Columbia River are designated as water quality limited for water temperature under Section 303(d) of the Clean Water Act (Figure 1). This designation arises from an analysis of data (Washington DOE, 1998) showing these waters do not meet water

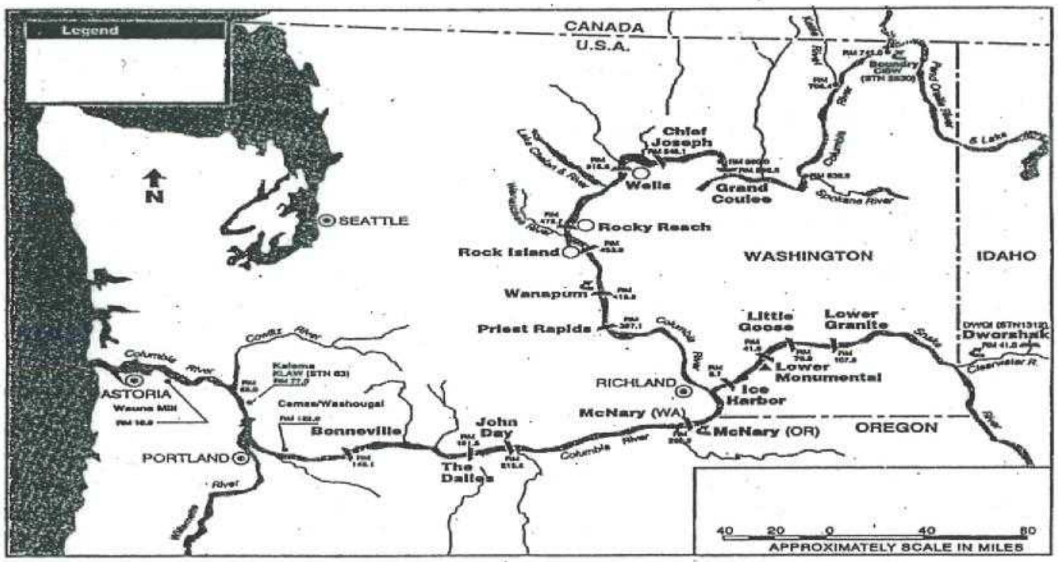

Figure 1. Map showing the Columbia and Snake Rivers and associated hydrolelectric projects in the study area.

quality standards for water temperature during all or part of the year. Sources, which may contribute to changes in the temperature regime of these segments of the Columbia and Snake Rivers, include:

(1) Construction of impoundments for hydroelectric facilities and navigational locks which increase the duration of time waters of the Columbia and Snake are exposed to high summer temperatures and which change the thermal inertia of the system

(2) Hydrologic modifications to the natural river system to generate electricity provide irrigation water for farmlands and to facilitate navigation.

(3) Modifications of watershed from agricultural and silviculture practices which reduce riparian vegetation, increase sediment loads and change stream or river geometry.

The objective of this work is to assess the relative importance of these sources with respect to changes in the temperature regime of the main stem Columbia River in Washington and Oregon and in the Snake River in Washington. This assessment will be part of the analytical framework and decision support system for developing management strategies to attain water quality standards and protect beneficial water uses in these rivers.

GEOGRAPHY, CLIMATE AND HYDROLOGY OF THE COLUMBIA BASIN

Geography

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the Pacific Northwest states of Idaho, Oregon, Washington and Wyoming. The Columbia River rises in the Rocky Mountain Trench and flows more than 400 miles through the rugged, glaciated mountains of southeastern British Columbia before it reaches the U.S.-Canada border near Castlegar, B.C. The Columbia River enters the U.S from the Okanogan Highland Province, a mountainous, area of Precambrian-early Paleozoic marine sediments. The Columbia crosses the western margin of the Columbia Basin, a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt and flows south across the state of Washington. Near Pasco, Washington and the confluence with the Snake River, the Columbia turns west, forming the border between the states of Oregon and Washington and flows more than 300 miles through the Casacade Mountain range to the Pacific Ocean near Astoria, Oregon.

The Snake River rises in Jackson Lake in the Teton Mountains of Wyoming at an elevation of 7000 feet above sea level. It flows east across the Snake Plain, which is also a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt. At the western boundary of the State of Idaho it turns north and flows through a deeply incised canyon, emerging near Lewiston, Idaho. At Lewiston, the Snake joins the Clearwater River and flows west through the Palouse Country of eastern Washington, joining the Columbia near Pasco, Washington. In addition to the Clearwater, major tributaries of the Snake in Idaho include the Bruneau, Owyhee, Boise, Payette, Weiser and Salmon Rivers.

In addition to the Snake River, the Columbia's largest tributary, other major tributaries include the Kootenai, Clark Fork-Pend Oreille, Spokane, Deschutes and Willamette Rivers. The Kootenai lies largely in Canada, but flows through western Montana, northern Idaho and back into Canada before entering the Columbia below Lower Arrow Lake in B.C. The Clark Fork-Pend Oreille has its headwaters on the Continental Divide in Montana, flows through northern Idaho into Pend Oreille Lake and becomes the Pend Oreille River. The Pend Oreille River flows north into Canada before joining with the Columbia River. The Flathead, Blackfoot and Bitteroot Rivers are all major tributaries of the Clark Fork. The Spokane River begins in Lake Coeur d'Alene in Idaho and flows west through eastern Washington, entering the Columbia in Lake Franklin D Roosevelt (Lake FDR). Both the Deschutes and Willamette River have their headwaters in Oregon, the Deschutes rising in central Oregon and flowing north across lava flows of the Columbia Basalt, while the Willamette River begins in the Cascade Mountains, flows west to the Willamette Valley, then north to join the Columbia near Portland, Oregon.

Climate

The climate of most of the Columbia River drainage is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while in some of the mountainous regions of Canada the annual precipitation can exceed 100 inches per year.

Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100° F for extended periods.

Temperatures at higher elevations remain cooler. Winters are cold throughout the basin and heavy precipitation falls in the form of snow in the mountain. The snowpack accumulates throughout the winter months as a result of frequent passage of storm systems from the Pacific Ocean. Some of the snowpack is incorporated into the extensive system of glaciers in the basin. However, beginning in May and June, much of the snowpack begins to melt giving rise to a hydrograph typical of a snowmelt regime.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all of the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing and summer air temperatures are seldom above 100° F for long periods. Average annual precipitation west of the Cascades is greater than 40 inches in most areas. Coastal stations are typically higher. Below about 5000 feet, most of the precipitation falls as rain with 70 percent or more falling between October and March.

Hydrology

Although the hydrology of the Columbia River system has been modified by the construction of numerous hydroelectric, irrigation, flood control and transportation projects, the hydrograph still has the characteristics of a snowmelt regime. Streamflows are low during the winter, but increase beginning in spring and early summer as the snowpack melts. Melting of the winter snowpack generally takes place in May and June, and streamflows increase until the snowpack can longer support high flows. Flows then recede gradually during the summer and flows are derived from reservoir storage and from ground water recession into the fall and winter.

Occasionally, runoff from winter storms augments the base flow and river discharge can increase rapidly. This is particularly true of the Willamette River, which occasionally reaches flood stage even with flood control available from system reservoirs.

Mean monthly and mean annual river discharges for key locations on the main stem Columbia and Snake River and selected tributaries are shown in Table 1.

WATER RESOURCES DEVELOPMENT

The Columbia River and its tributaries have been developed to a high degree. The only segment of the Columbia River above Bonneville Dam which remains unimpounded is the Hanford Reach between Priest Rapids Dam (Columbia River Mile 397.1) and the confluence with the Snake River (Columbia River Mile 324.3). The 11 main stem hydroelectric projects in the U.S. (Table 2), from Grand Coulee Dam to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head. Hydroelectric and flow control projects on the main stem of the Columbia River and its tributaries in Canada have resulted in significant control of flow in the Upper Columbia and Kootenai River Basins. The Snake River is also nearly fully developed with a total of 19 dams on the main stem as well as a number of impoundments on tributaries.

These dams and reservoirs serve many purposes, including irrigation, navigation, flood control, municipal and industrial water supply, recreation and generation of hydroelectric power. There are approximately seven million acres of irrigated farmlands in the Columbia River Basin, including 3.3 million acres in Idaho, 0.4 million acres in Montana, 1.9 million acres in Washington and 1.3 million acres in Oregon (BPA et al, 1994). The systems has a capacity for generating more than 20,000 megawatts of hydroelectric energy and slack-water navigation now extends from the mouth at Astoria, Oregon to Lewiston, Idaho, a distance of more than 460 river miles.

In the U.S., the ownership of the dams in the Columbia River Basin includes federal agencies, private power companies, and public utility districts. The Columbia Treaty between the

United States and Canada provides the basis for managing transboundary issues related to the operation of dams and reservoirs on the Columbia River system in Canada.

WATER QUALITY ISSUES

Water quality issues in the Columbia River Basin reflect the diversity and complexity of the system. Although the quality of water is relatively high in most of the main stem Columbia, beneficial uses of aquatic resources in the Columbia River Basin are impaired in many segments due to point source pollutant loading from industries and municipalities and nonpoint source loadings from timber harvest, agriculture, mining and urban runoff. Modification of the hydrologic regime and alterations of riparian and terrestrial areas have also contributed to water quality degradation throughout the system.

The nature of water quality problems in the main stem Columbia and Snake Rivers in Washington is described in the list of water quality-limited segments prepared by The State of Washington's Department of Ecology. This list was prepared as part of the review of water quality under Section 303 (d) of the Clean Water Act, which requires that each state identify those waters within its boundaries for which water quality standards and beneficial uses are not being attained. In those segments listed under this section, the state is required to establish a total maximum daily load (TMDL) for those pollutants contributing to the impairment of beneficial uses. The listing of these water quality parameters in Water Resource Inventory Areas (WRIA's) comprising the main stem Columbia and Snake Rivers in the State of Washington is given in Table 3. In addition, a TMDL has been established on the main stem Columbia and Snake Rivers to control dioxin, an organic toxicant associated primarily with pulp mills that use chlorine to bleach paper products.

Many of parameters on the Candidate 1998 Section 303 (d) List are associated with the operation of hydroelectric facilities and nonpoint source pollution from mining and agriculture. Two of the most frequently occurring parameters on the list are total dissolved gas and water temperature. According to the Columbia River System Operation Review (BPA et al, 1994), water released over spillways of dams can increase the level of dissolved gas in the water, which in turn causes gas bubble disease in fish. The System Operation Review also notes that dams modify the temperature regime of natural rivers. Changes in temperature and gas pressure of water released from hydroelectric projects have an impact on the aquatic ecosystem of the Columbia River system, particularly on migrating salmon and steelhead. Mortality rates for these species increase with increasing water temperatures and dissolved gas levels. This is important because several species and sub-species of salmon and steelhead in the Columbia River system have been listed as threatened or endangered under the Endangered Species Act (ESA).

Understanding the dynamics and predicting levels of total dissolved and water temperature is essential for attaining water quality standards and protecting beneficial uses in the Columbia River. A great deal of scientific effort has been devoted to this task in the Columbia River system, as well as in other aquatic environments. However, these efforts have not, as yet, been put in the context of a TMDL, as required for water bodies listed as water quality limited under Section 303 (d) of the Clean Water Act.

STUDY OBJECTIVES

One of the first steps in developing a TMDL is an assessment of the problems associated with a given water quality parameter(s). The purpose of an assessment is to identify the sources for the water quality parameter of concern and what, if any, control or management strategies are possible. In this study, water quality models for water temperature are used to provide some of the framework for a problem assessment of the main stem Columbia from the International Boundary to Bonneville Dam and of the Snake River from its confluence with the Clearwater River near Lewiston, Idaho to its confluence with the Columbia River near Pasco, Washington.

Barnwell and Krenkel (1982) have characterized the use of water quality models as management decision support tools in the context of screening, planning, and design (Barnwell and Krenkel, 1982). In their taxonomy, screening models are used to satisfy the requirement for rapidly assessing either an extensive geographical area or a large number of water quality parameters. The output of screening models is for the purpose of identifying marginal and critical areas for additional study.

The objectives of this study are to develop and implement a mathematical model of water temperature for the Columbia and Snake Rivers in a way that is generally consistent with those of the screening model, at least in terms of the level of certainty required for the model output. That is, the output from the water temperature models will be used to identify critical areas for additional analysis. However, given the geographical scale and complex nature of the hydrologic and meteorological environment of the Columbia River system, the study objectives require a level of spatial and temporal complexity which is greater than for the screening models described by Barnwell and Krenkel (1982). In addition, effort will be devoted to quantifying the uncertainty of model output.

MATHEMATICAL MODEL DEVELOPMENT

System Boundaries

The boundaries of the Columbia River system included in the assessment of water temperature, as described previously, include the Columbia River from the International Border (R.M. 745.0) to Bonneville Dam (R.M. 145.5) and the Snake River from its confluence with the Clearwater River near Lewiston, Idaho (R.M. 139.9) to its confluence with the Columbia River near Pasco, Washington. With the exception of Grand Coulee Dam and its impounded waters, Lake FDR, all the hydroelectric projects on these segments of the Columbia and Snake Rivers have limited storage capacity and are operated as run-of-the-river reservoirs. Because of its large storage capacity (Table 2), Lake FDR is used for flood control as well as for irrigation and generation of hydroelectric power. Reservoir elevations for Lake FDR show a substantial annual variation (Figure 2).

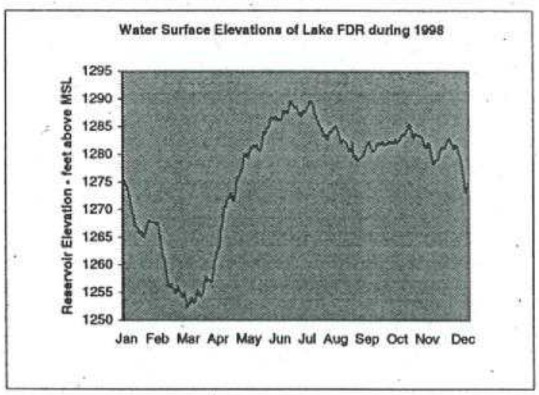

Figure 2. Surface elevations in Lake Franklin D Roosevelt during 1998

Run-of-the-river reservoirs are those for which reservoir elevation is kept more or less constant and water coming in to the reservoir is passed directly through the reservoir. Reservoir elevations in Lower Granite Reservoir and John Day Reservoir, the two largest run-of-the-river reservoirs on the Snake and Columbia Rivers, respectively, are shown in Figures 3 and 4.

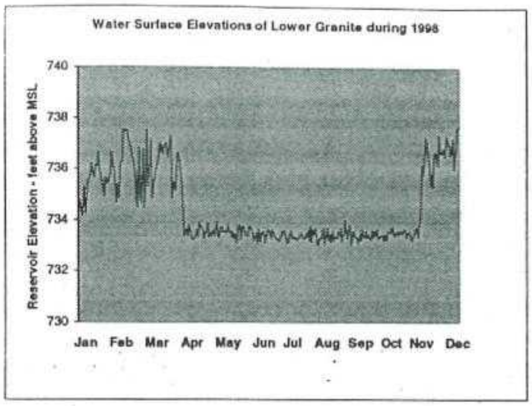

Figure 3. Surface elevations in Lower Granite reservoir during 1998

The differences between the run-of-the-river reservoirs and Lake FDR, with respect to both their modes of operation and storage capacity, give rise to differences in their respective thermal regimes. For the run-of-the-river reservoirs, the spatial variability of temperature within a cross-section perpendicular to the direction of flow is generally less than 1^0 C (McKenzie and Laenen, 1998). In Lake FDR, vertical variations in water temperature of up to 5 ^{0}C have been at various locations along the longitudinal axis of the reservoir. Because of this difference in the thermal regimes, the run-of-the-river projects can be modeled as systems with variability in the longitudinal direction, only. Lake FDR, however, will be treated as a system with both vertical and longitudinal spatial variability. This report describes the thermal energy model for the run-of-the-river reservoirs.

The system boundaries for the model of the run-of-the-river segments are from the tailwaters of Grand Coulee Dam (Columbia R.M. 596.6) to Bonneville Dam (Columbia R.M. 145.5) and from Snake R.M. 139.0 to Snake River 0.0. Only the main stems are included specifically in the analysis of these segments. However, the advected thermal energy from major sources tributary (Table 4) to these segments is included in the analysis.

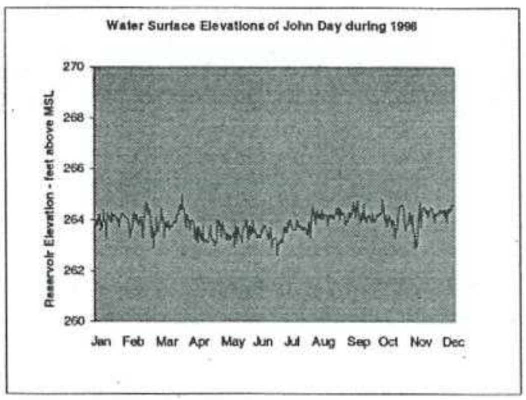

Figure 4. Surface elevations in John Day reservoir during 1998.

Thermal Energy Budget

The thermal energy budget method has proven to be a useful concept for simulating temperatures in aquatic environments. Concern regarding the impact of reservoir operations on water temperature and aquatic ecosystems provided the motivation for early applications of the method (Burt, 1958; Delay and Seaders, 1966; Rafael, 1962; Edinger et al., 1974; Peterson and Jaske, 1968). Prior to the passage of the Clean Water Act, numerous studies of the thermal discharges by the electric power industry were also performed using the energy budget method (Peterson and Jaske, 1968; Edinger et al, 1974). Brown (1969, 1970) applied the method to simulating stream temperature increases resulting from the removal of riparian vegetation during logging operations. Recent applications of the energy budget method have focussed on water quality planning issues related to reservoir operations (Cole and Buchak (1995), watershed management (Foreman et al, 1998; Risley, 1997; Rishel et al, 1982; Sinokrot and Stefan, 1993) and fisheries habitat enhancement (Bartholow, 1989; Theurer et al, 1984).

Thermal energy budget models for aquatic ecosystems are developed either in an Eulerian frame of reference, in which the reference system is fixed in space and through which the water flows; or a Lagrangian frame of reference in which the reference system moves with the fluid. The one-dimension thermal energy model for estimating the state variable, water temperature, stated in terms of the Eulerian viewpoint and assuming there is no longitudinal dispersion is:

$$\rho C_p A_x \frac{\partial T}{\partial t} + \rho C_p \frac{\partial (QT)}{\partial x} = w_x H_{net} + S_{adv} + w_T \tag{1}$$

where,

ρ = the density of water, kg/meter^3,

C_p = the specific heat capacity of water, kcal/deg C/kg,

A_x = the cross-sectional area of the river at the distance, x, meter^2,

T = the water temperature, deg C,

Q = the river flow rate, meter^3/second,

w_x = the width of the river at the distance, x, meters,

H_{net} = the heat flux at the air-water interface, kcal/meter^2/second,

S_{adv} = the heat advected from tributaries and point sources, kcal/meter/second,

w_T = a random water temperature forcing function, $\sim N(0, \Sigma_Q(t))$

x = the longitudinal distance along the axis of the river, meters,

t = time, seconds.

In the Lagrangian frame of reference the one-dimensional thermal energy model, the systems model for estimating the water temperature, assuming no longitudinal dispersion, is given by:

$$\rho C_p A_x \frac{dT}{dt} = w_x H_{net} + S_{adv} + w_T \qquad (2)$$

where the symbols are as previously defined.

Equations 1 and 2 are the state-space system equations for water temperature in the Eulerian and Lagrangian frame of references, respectively. Water temperature measurements also provide an estimate of the system state. The observation model for water temperature at the k^{th} time interval is given by (Gelb, 1974)

$$Z_k = H_k T_k + v_k \qquad (3)$$

where,

Z_k = the measured value of the water temperature, °C,

H_k = the measurement matrix,

v_k = the measurement error, $\sim N(0, \Sigma_R)$

Σ_R = the variance of the measurement error, v_k.

Heat Exchange Across The Air-Water Interface

Heat exchange across the air-water interface is generally the major source of thermal energy for lakes, rivers and reservoirs. As is the case for the applications described above, this study assumes the net exchange of thermal energy, H_{net}, across the air-water interface can be described by:

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) + H_{evap} + H_{cond} - H_{back} \qquad (4)$$

where,

H_{net} = Net heat exchange across the air-water interface, kcal/meter^2/second,

H_s = Shortwave solar radiation, kcal/meter^2/second,

H_{rs} = Reflected shortwave solar radiation, kcal/meter^2/second,

H_a = Longwave atmospheric radiation, kcal/meter^2/second,

H_{ra} = Reflected atmospheric radiation, kcal/meter^2/second,

H_{evap} = Evaporative heat flux, kcal/meter^2/second,

H_{cond} = Conductive heat flux, kcal/meter^2/second,

H_{back} = Blackbody radiation from the water surface, kcal/meter^2/second.

Solution Method

The goal of the solution method is to obtain an optimal estimate of the state variable, water temperature. The Kalman filter (Gelb, 1974; Schweppe, 1974) provides a recipe for combining state estimates from a linear systems model (equation 1 or equation 2) with estimates from the observation model (equation 3) to give the best linear unbiased estimate of the system state.

When there are measurements available, the recipe calls for obtaining a solution to the systems model and combining the solution with the observation. The two estimates are combined using a weighting factor determined by the relative uncertainty of the systems model compared to the uncertainty of the observation model. The weighting factor, the Kalman gain matrix, is derived by constraining the error in the estimate to be unbiased and to have a minimum mean square error. For linear systems, the complete Kalman filter algorithm is

System Model:	$\underline{T}_k = f_{k-1}\, \underline{T}_{k-1} + \underline{w}_{k-1}$	$\underline{w}_k \sim N(\underline{0}, \Sigma_Q)$	(5)
Measurement Model:	$\underline{T}_k = H_k\, \underline{T}_k + \underline{v}_{k-1}$	$\underline{V}_k \sim N(\underline{0}, \Sigma_R)$	(6)
System Extrapolation:	$\underline{T}_k(-) = f_{k-1}\, \underline{T}_{k-1}(+)$		(7)
Error Covariance Extrapolation:	$P_k(-) = f_{k-1}\, P_{k-1}(+) f_{k-1} + \Sigma_Q$		(8)
State Estimate Update:	$\underline{T}_k(+) = \underline{T}_k(-) + K_k[\underline{z}_k - H_k\, \underline{T}_k(-)]$		(9)
Error Covariance Update:	$P_k(+) = [I - K_k H_k]\, P_k(-)$		(10)
Kalman Gain Matrix:	$K_k = P_k(-) H_k^T [H_k\, P_k(-) H_k^T + \Sigma_R]^{-1}$		(11)
Innovations Sequence:	$v_k = z_k - H_k T_k(-)$		(12)

Where (-) denotes values at time, k, prior to filtering, (+) denotes values at time, k, after filtering and f_k is the systems matrix.

To obtain an estimate of the water temperature from the systems model, it is first necessary to decide whether to implement the solution method with a Lagrangian point of view or with an Eulerian point of view. Given the spatial and temporal complexity of the natural environment, most mathematical models using the thermal energy budget method are developed in the Eulerian frame of reference. The Eulerian frame of reference is a more intuitive way of viewing changes in concentrations simply because most measuring devices are fixed at a specific location rather than moving with the water. It is also less difficult to incorporate spatial complexity into the Eulerian framework, and, therefore, easier to add more spatial dimensions as well as more complex spatial processes such as dispersion and turbulent diffusion.

Most systems models using the Eulerian framework solve equation 1 with either finite difference (Brown and Barnwell, 1987; Cole and Buchak, 1995; Sinokrot and Stefan, 1993; Smith, 1978) or finite element methods (Baca and Arnett, 1976). These models have generally proved valuable for simulating water temperatures in a variety of aquatic environments. However, it is well known that solutions to equations of the type characterized by equation 1, using finite difference or finite element techniques, are subject to stability and accuracy problems (e.g., O'Neill, 1981). For water quality models, stability problems are generally not as serious as accuracy problems. When a solution becomes unstable, it is usually obvious and can generally be eliminated by reducing the time step. Accuracy problems are more pervasive and often subtle. Of particular concern to developers of finite difference and finite element methods are problems associated with the propagation of phenomena with short wavelengths. They are most evident in the propagation of sharp spatial gradients when advection dominates the system. The resulting simulations can have spurious damping of high frequencies or oscillations. They are caused by differences between the rate at which the numerical scheme propagates the solution in space and the rate at which the solution would be propagated in space by the natural system.

Solution techniques based on the Lagrangian point of view (Jobson, 1981) avoid the accuracy problems associated with Eulerian methods but lack the computational convenience of a fixed grid. However, efficient accurate solution methods have been proposed which combine the virtues of each point of view (Cheng et al; 1984; ~~Yeh, 1990~~; Zhang et al, 1993). In these hybrid Eulerian-Lagrangian methods, advective processes are treated with a Lagrangian formulation. Diffusion processes are treated with an Eulerian formulation. Valocchi and Malmstead (1992) have shown that operator splitting of this kind can provide accurate solutions to advection-diffusion-reaction problems when the reaction term is sufficiently small.

Although diffusion-like processes are being neglected in this analysis, the mixed Eulerian-Lagrangian method was chosen as the solution technique for simulating water temperature in the Columbia River system for the following reasons:

- It provides flexibility to expand scope of model to include diffusion-like processes and/or more spatial dimensions.
- It is relatively easy to avoid instabilities in the solution when the Courant stability criterion is exceeded.
- It reduces the state-estimation (filtering and prediction) problem to one of a single state variable rather than one requiring a state variable for each finite difference or finite element grid point.

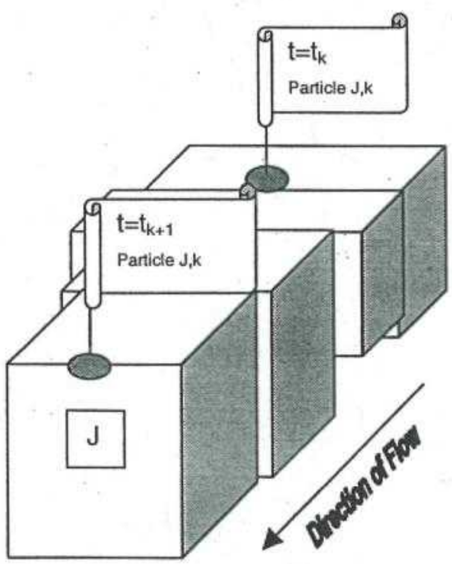

Figure 5. Schematic for reverse particle tracking method

The mixed Eulerian-Lagrangian method uses the concept of reverse particle tracking to implement the Lagrangian step. The river system is divided into N segments, not necessarily of the same spatial dimensions. Within each segment, however, the geometric properties of the river system are assumed to be constant during a given time step. Water temperature values are recorded only on the boundaries between segments. As an example of the method, consider the Segment J. (Figure 5). At the end of a computational time step, $t = t_{k+1}$ a particle at the downstream end of the Segment J, is flagged. The flagged particle is tracked backward in time upstream until its position at the beginning of the time step, $t = t_k$, is located. The location of a particle tracked in this manner will, in general, not be precisely on a segment boundary, where water temperatures are stored by the computational scheme. Therefore, it is necessary to determine the water temperature of the particle at the beginning of the time by interpolating between the points where water temperatures are recorded. In the solution technique used in this study, this is accomplished with a second-order polynomial using Lagrangian interpolation (Press et al, 1986). Once the location of the particle and its initial water temperature are determined for the beginning of the time step, the particle is followed back downstream to its location at the end of the time step (the downstream end of Segment J). The change in water temperature for the particle during this time step is estimated using equation 2

The information required to obtain a solution to equation 2 using reverse particle tracking includes

- River width as a function longitudinal distance during the time step
- Cross-sectional area as a function of longitudinal distance during the time step
- River velocity as a function of longitudinal distance during a time step
- Net heat exchange as a function of longitudinal distance during a time step.

The hydraulic characteristics of the unimpounded reaches of the river system are estimated from power equations relating mean velocity, area and width (Leopold and Maddock, 1953). That is,

$$U = A_u \, Q^{B_u} \tag{13}$$

$$A_x = A_a \, Q^{Ba} \tag{14}$$

$$W_x = A_w \, Q^{B_w} \tag{15}$$

where,

U = the river velocity, feet/second,

A_x = the cross-sectional area, feet^2,

W_x = the river width, feet,

The coefficients, A_u, B_u, A_d, A_u, B_u, A_w, and B_w, are estimated by simulating river hydraulics conditions under various flow conditions using the methods of steady gradually varied flow (HEC, 1995). The gradually varied flow method gives estimates of U, D, and W_x as a function of river flow. The coefficients are determined by fitting equations 13-15 to the resulting estimates using the method of least squares.

For the impounded reaches, the water surface elevation is assumed to remain constant, such that the depth and width remain constant at any cross-section and the velocity, U, is simply

$$U = Q/(W_x{}^*D) \qquad (16)$$

Exchange of thermal energy across the air-water interface is estimated from Eq. (3) using formulations for components of the heat budget as described by WRE (1968).

Time and Length Scales

To accomplish the management objectives of the analysis it is necessary to simulate daily-averaged water temperatures as a function of longitudinal distance in the Columbia and Snake Rivers. This establishes an approximate lower limit on system time scales and on data requirements. Stability and accuracy issues associated with solutions to Eq. (3) can impose a requirement of even smaller time increments to obtain reliable solutions. However, the simulated results for time scales less than a day are valuable only in terms of their contribution to the solution accuracy. Since the time scale of the input data is equal to or greater than one day, there is no physical significance to higher frequency output associated with the need to obtain a stable solution.

In an effort to include the environmental variability due to hydrology and meteorology, the largest time scales are of the order of two decades. This time scale is constrained by the hydrologic data available for the Columbia River system under existing management. Existing management in this case means operation of the system subsequent to the construction of the last hydroelectric project (Lower Granite, 1975)

The length scales for the analysis are determined by a number of factors. These include the availability of geometric data, spatial variability in the river geometry and computational stability and accuracy. It is often the case that data availability provides the most severe constraint. However, in the case of the Columbia and Snake Rivers, within the boundaries of this analysis, there are ample data for describing river geometry in both rivers. The primary factor determining the length scale of this analysis is the need to achieve stable, accurate solutions. Length scales are such that the time it takes a parcel of water to traverse a given computational segment is always equal to or less than one day. For the Columbia and Snake Rivers, this results in length scales of the order of 1 to 10 miles.

Rationale for Approach

Idealizing the largest part of the Snake and Columbia River system in terms of a one-dimensional model is based on the assumption that a simple model will capture the major features of the water temperature regime in the two large rivers. This is in keeping with the management objective of providing a primary temperature assessment for developing a TMDL. The simple one-dimensional model described above is relatively easy to implement. Based on previous work in the Columbia and Snake Rivers (Rafael, 1962; Yearsley, 1969; Jaske and Synoground, 1970), a simple model of this type should capture the major features of water temperature impacts in this system. The mixed Lagrangian-Eulerian scheme for handling advection was chosen based on studies such as those done by Yeh (1990) and Zhang et al (1993)

DATA SOURCES

Water Temperature

The extensive water temperature data records for the Columbia and Snake River have been assembled and reviewed for quality by Tony Laenen and Stuart McKenzie (Laenen and McKenzie, 1998). In addition, Laenen and McKenzie (1998) organized the data in electronic formats for rapid analysis. The results of their work provide a water temperature data set for the Columbia and Snake Rivers, which can be used to describe temperature model uncertainty. The data quality analysis performed by Leanen and McKenzie (1998) provides a basis for characterizing the uncertainty associated with the measurements.

McKenzie and Laenen (1998) compiled data for the main stem Columbia and Snake Rivers. Temperature data for the tributaries included in the analysis were obtained from observations made by the Idaho Power Company, Washington State Department of Ecology (DOE) and the U.S. Geological Survey (USGS). The location of monitoring locations, period of record and frequency of analysis are shown in Table 4.

River Geometry

River geometry is needed to characterize the hydraulic properties of the river as a function of flow and time. The basic data required is elevation of the river channel above mean sea level at a sufficient number of cross-sections so as to adequately describe water depth, water width and velocity as a function of river flow. A number of sources were used to accomplish this. These sources are described in Table 5.

Hydrology

River hydrology data for the main stem Columbia and Snake Rivers, as well as the major tributaries were obtained from the records maintained by the U.S. Geological Survey. Gaging stations used in the study are shown in Table 6.

Meteorology

Meteorological data, including station pressure, cloud cover, wind speed, air temperature and relative humidity, are required for the thermal energy budget calculations. Stations in the Columbia basin with these data include Lewiston, Idaho, Spokane, Washington and Yakima, Washington. Data are available for these locations at three-hour intervals from the NCDC SAMSON data sets. The period of record for each of these stations is shown in Table 7.

Stations with maximum and minimum daily air temperatures are more numerous and are included in the NCDC Local Climatological Data Sets. Air temperature data from these stations were used in conjunction with the regional meteorological stations (Table 8) to develop synthetic records on a local scale.

PARAMETER ESTIMATION

The parameter estimation process addresses both the deterministic and probabilistic parameters in the model. The deterministic elements include the source term, f_k, and, implicitly, the travel times of parcels in the Lagrangian reference system. The components of the heat budget (equation 4) and the advected thermal inputs from tributaries comprise the source terms. The parameters required to determine the travel times are derived from an analysis of the system hydraulics. It should be noted these parameters are, in fact, not really deterministic. They are, in fact, random variables. However, for the purposes of this analysis the composite error resulting from variability in the so-called deterministic parameters is included in the error term, w_Q, in equation 5. Given this assumption, the probabilistic parameters are the means and variances of the error terms for the measurement model and the systems model.

In this study, the parameter estimation process is implemented in three steps. In the first step, the deterministic parameters are estimated, ideally, from first principles or, as is more often the case, from available research. Next, the deterministic parameters estimated in this way are adjusted until the simulated results from the systems model are approximately unbiased. The systems model is unbiased if the mean of the innovation vector is small, where the innovation vector is the difference between time-updated simulations from the systems model and the actual measurements (Van Geer et al, 1991). Assuming the actual measurement bias and their variances are known, the final step in the parameter estimation process is to estimate the variance, Σ_Q, of the systems model.

Hydraulic Coefficients

As described previously, the hydraulic properties of each unimpounded river segment are estimated from relationships of the type given in equations 13-15. One of the primary objectives of the study is to assess the impact of impoundments. It was, therefore, necessary to make estimates of these coefficients for two states of the system; one with dams in place and for one with all the dams removed. For the case in which the dams were in place, the results from the USACE HEC-5Q model of the Columbia and Snake Rivers were provided by Nancy Yun of the USACE North Pacific Division Office and are given in Tables A-1 and A-2, Appendix A. The only impounded reach under the present configuration of impoundents is the Hanford Reach. The coefficients in equations 13-15 for the Hanford Reach are given in Table A-3, Appendix A.

For the scenario with dams removed, geometric properties of the Columbia and Snake Rivers, obtained from the sources given in Table 5, were used as input data to HEC-RAS (USACE-HEC, 1995), the steady gradually varied flow model developed by the US Army Corps of Engineers Hydrologic Engineering Center. Surface elevations of the Columbia and Snake Rivers were estimated for flows of 150,000, 250,000 and 500,000 cfs in the Columbia River and 60,000, 120,000 and 240,000 cfs in the Snake River. For each of these flows, the average water depth, surface width and velocity at selected locations was used to estimate the coefficients in equations 13-15 using the methods of least squares. The coefficients obtained in this manner are given in Table A-4 and A-5, Appendix A.

Water Balance

The daily flow at any location in either river was determined from the sum of the daily gaged flow of the main stem headwaters and the tributaries upstream from the location. This assumes that

- information regarding flow changes is transmitted instantaneously to locations downstream.
- Tributary sources other than those shown in Table 4 are negligible.

Heat Budget

The specific form for each of the terms in the heat budget formulation (equation 4), as used in this and most other studies involving the energy budget method, is based on a compilation of heat budget studies by Wunderlich and Gras (1967). Chapra (1997) and Bowie et al (1985) also have comprehensive discussions of each of the terms in equation 4 adapted from Wunderlich and Gras (1967). From the work of Wunderlich and Gras (1967), the individual elements of the heat budget are given by

Shortwave (Solar) Radiation

$$(H_s - H_{rs}) = F(\Phi, \delta, D_y) \tag{17}$$

where,

Φ = the latitude of the site,

δ = the declination of the sun at the site,

Dy = the day of the year.

Longwave (Atmospheric) Radiation

$$(H_a - H_{ra}) = (1-\alpha_{ar})\ 1.23 \times 10^{-16}\ (1.0 + 0.17\ C^2)\ (T_{DB} + 273.)^6 \tag{18}$$

Evaporative Heat Flux

$$H_{evap} = \rho * \lambda * E_v * W * (e_o - e_a) \tag{19}$$

Conduction Heat Flux

$$H_{cond} = R_B \left[\frac{T_S - T_a}{e_s - e_a} \right] \frac{p_a}{1013.3} \tag{20}$$

Black Body (Water Surface) Radiation

$$H_{back} = 0.97\ \sigma\ (T_s + 273.)^4 \tag{21}$$

Initial Water Temperatures

Daily water temperatures are not always available for the locations used as initial conditions on the main stem Columbia and Snake Rivers or for the input conditions for important tributaries (Table 4). For most stations long-term sampling with a period of two to four weeks provides sufficient data to synthesize stream temperatures using air temperature. In their study of 584 USGS stream gaging stations within the contiguous United State, Mohseni et al (1998) used a nonlinear model of the following type to synthesize water temperatures

$$T_s = \mu + \frac{\alpha - \mu}{1 + e^{\gamma(\beta - T_a)}} \tag{22}$$

where,

T_s = the weekly stream temperature,
T_a = the weekly air temperature from a nearby weather station and

α, β, γ and μ are determined by regressing the observed water temperature data on the air temperature data by minimizing the squared error with the downhill simplex method (Nelder and Mead, 1965).

Separate functions of the type defined in equation 22 are used to describe the rising limb and the falling limb.

Mohseni et al (1998) concluded that the method was accurate and reliable at 89% of the streams. Mohseni et al (1998) also found that the method gives good results even when the air temperature measurements were not in proximity to the stream gaging locations.

For the analysis of the Columbia and Snake Rivers, some adjustments were made to the method by constraining certain parameters in equation 22. The resulting parameters, for both rising and falling limbs, at each of the input locations, are given in Table 9.

Measurement Bias and Error

The analysis of water temperature in the Columbia and Snake Rivers by McKenzie and Laenen (1998) provides the basis for estimating the probabilistic parameters of the measurement model (equation 3). The data reviewed by McKenzie and Laenen (1998) were obtained from scroll case measurements and measurements made in conjunction with total dissolved gas monitoring. The scroll case measurement reflects the temperature of the water as it enters the generating turbine and is measured by reading the level of a mercury thermometer. The total dissolved gas monitoring program uses a temperature probe located in the forebay of each of the dams and at a depth generally equal to or greater than 10 feet.

The quality, bias, and variability of these data vary considerably from site to site. For the scroll case data, McKenzie and Laenen (1998) report frequent "stepping" of the data. Stepping is characterized by periods of several days when the reported temperature is constant. Scroll case temperatures are measured by visual observations from mercury thermometers and recorded manually, generally on a daily basis. McKenzie and Laenen (1998) suggest that the measurement method may have contributed to "stepping" and may have been due to the frequency with which scroll case temperatures were made and reported in the past.

The variation in data quality makes the task of quantifying measurement bias and error a difficult one. McKenzie and Laenen (1998) report bias in the measurements as high as 2.0 °C and variability as high as 2.0 °C at certain sites and during certain periods of the year. However, at most sites and for recent data (post–1990), bias is in the range 0.0-1.5 °C and variability is generally less than 1.0 °C.

Systems Model Bias and Error

The approach to estimating the probabilistic parameters for the systems model (Eq. (5)) follows that of Van Geer et al (1991). Initial estimates of deterministic parameters are obtained from some combination of first principles and existing research. This includes the heat transfer across the air-water interface, advected thermal energy from tributaries and point sources and hydraulic properties of the river system. Adjustments are made to certain parameters until the mean of the innovations vector (equation 12) is small.

The parameters selected for adjustment are constrained by assuming that any error in the basic heat transfer components (equations 17-21), the advected energy from tributaries and the hydraulic computations can be aggregated into the systems model error, $\Sigma_Q(t)$. Given these constraints, what remains to be adjusted is the choice of meteorological stations used to estimate the basic heat transfer components.

Data from two classes of meteorological stations are available to estimate these components as described previously. There are a limited number of Surface Airways (SAMSON) stations reporting the complete suite of meteorological variables. There is extensive coverage of daily maximum and minimum air temperatures from the Local Climatological Data (LCD) . Data from the SAMSON stations were used to expand the spatial coverage for heat budget analysis. This was accomplished by assuming that wind speed, cloud cover, relative humidity and station pressure are large-scale phenomena and that air temperature is more of a local phenomenon. Several LCD stations were augmented with SAMSON data in this way to provide more spatial coverage of the surface heat transfer. Meteorological data were assigned to river segments based on a qualitative assessment of local meteorology. A number of combinations of stations were evaluated in an effort to achieve unbiased simulations. The final configuration of stations, giving rise to the results shown in Figures 6-13, is given in Table 10.

Using parameters estimated above, estimates of the system model error variance, $\Sigma_Q(t)$, are obtained by adjusting the estimated variance until the theoretical variance for the innovation vector is approximately equal to the sample variance (Mehra, 1972). The theoretical variance is given by (Kailath, 1968):

$$E\{v_k v_k^T\} = H\,P_k(-)\,H^T + \Sigma_R \tag{23}$$

and the sample variance, S, by

$$S = \frac{1}{m}\sum_{k=1}^{m} v_k v_k^T \tag{24}$$

This is an iterative process since the innovations vector is a function of the deterministic parameters and the probabilistic parameters. In addition, there is bias and error in the observations (McKenzie and Laenen, 1998) as described previously . The systems model error estimate was obtained by first finding a set of meteorological stations which provided good (in a qualitative sense) agreement. This was followed by an adjustment of measurement bias and error for the scroll case temperature data, within the range estimated by McKenzie and Laenen (1998). The results of this process for the mean of the innovations sequence are shown in Figures 14-21. The theoretical and sample variance for the innovations sequence are compared in Figures 22-29. The final values for systems model variance, Σ_Q, and measurement error and bias are given in Table 11.

MODEL APPLICATION

Scenarios

The goals of this study are to assess the relative contribution of impoundments and tributary inputs to changes in the thermal regime of the Columbia and Snake Rivers. To capture the environmental variability in hydrology and meteorology, the 21-year record of stream flows and weather data from 1975 to 1995 is used to characterize river hydraulics and surface heat transfer rates. Tributary temperatures are developed from local air temperatures using the relationship given by equation 22 and air temperature data for the same 21-year period. The assessment of impacts to the thermal regime of the Columbia and Snake River is based on the following three scenarios

- Scenario 1 This scenario includes the existing configuration of dams, hydrology and meteorology for the period 1975 to 1995 and tributary temperatures estimated from the 21-year meteorologic record using equation 22
- Scenario 2 This scenario assumes all the dams on the Columbia River downstream from Grand Coulee have been removed and the four lower dams on the Snake Have been removed. Hydrology, meteorology and tributary temperatures are the same as Scenario 1.
- Scenario 3 This scenario assumes existing configuration of dams, with hydrology and meteorology for the period 1975 to 1995. Tributary input temperatures are estimated from the 21-year meteorologic record using equation 22, but are not allowed to exceed 16 °C.

For each of these scenarios, daily-averaged water temperatures are simulated and the mean, mean plus one standard deviation, and the mean minus one standard deviation of the simulated water temperatures are compared to the benchmark, 20 °C. The average annual duration with which the simulated temperature exceeds the benchmark, estimated as the number of days of exceedance compared to the total number of days in the simulation, is used as one measure for assessing temperature impacts. Another measure is the average value of the exceedance for each of the three simulation types. The standard deviation for these simulation is computed with the Kalman filter (equations 5-11) in the prediction mode. In the prediction mode, the measurement matrix, H, is set to zero. This means the Kalman gain, K, is always zero and the variance propagation is a result of updating by the systems model only:

$$\Sigma_k = f_{k-1} P_{k-1} f_{k-1}^T + \Sigma_Q \qquad (25)$$

where the (+) and (-) convention has been dropped since there is no updating based on the observations.

The frequency with which the simulated daily-averaged temperatures exceed the benchmark are plotted for each scenario as a function of Columbia and Snake River Mile in Figures 30-35. The error bars in each of the plots represent the frequencies estimated with the simulated means plus one standard deviation and the simulated means minus one standard deviation. The corresponding results for the average magnitude of excursions above the benchmark are shown in Figures 36-41.

Uncertainty and Variability

The objective of this study was to develop a model of water temperature in the main stem Columbia and Snake Rivers for the purpose of identifying critical issues for additional study. The scale of important system dynamics is complex in both time and space and the focus in this study was on the space-time complexity rather than on model complexity. The nature of the objectives and the limitations associated with the observations and knowledge of systems dynamics may introduce additional uncertainty and variability into the final results. The analysis method was developed to characterize some of that uncertainty and variability. However, there are a number of issues, which deserve attention in subsequent analyses of water temperature in the Columbia and Snake Rivers. These issues include:

- Heat budget - The choice of meteorologic stations to characterize the energy budget was done subjectively, to achieve good (in a qualitative sense) agreement between simulated values and observations. The analysis would benefit from additional studies of the effect of local climatology, particularly wind speed.

- River hydraulics - Particle displacement speeds and system geometry were based on the assumption that gradually varied, steady-state flow methods were appropriate. This assumption is probably reasonable for the scenarios for which the dams are in place and less so for the river without dams. The uncertainties associated with rapidly changing flows are likely to be greatest during the spring and early summer snowmelt periods. It less likely they will be important during the critical late summer and early fall periods when flows are low and reasonably steady.

- Initial water temperatures - Initial conditions for water temperature of both main stem and tributatries were estimated by regressing observed water temperature data on the week air temperature data and obtaining a fit to equation 22 which minimizes the squared error. The error introduced as a result of this simplification is greatest for the main stem temperatures, since the results of the analysis show that the tributaries have little impact on the average temperatures of the Columbia and Snake Rivers. The error introduced in the main stream estimates will decrease in the downstream direction.

- Water Balance – The system water balance was derived from flows measured at gaging stations on the main stem Columbia and Snake Rivers and their major tributaries in the study area. Withdrawals for irrigation, groundwater return flow and miscellaneous tributary flow were not included in the water balance. These sources comprise an estimated 5-7% of the flow increment to the Columbia River. The groundwater component may well be the most important component not included in the analysis, since groundwater temperatures are likely to be lower than the main stem in the summer and higher during the summer

- Filter - The estimation of the systems model error is based on the assumption the filter is optimal. The filter is optimal if the innovations sequence is a zero mean, Gaussian white noise process. Tests for optimality of the filter have been described by Mehra (1970). These tests were not performed on the water temperature innovations sequence, but a visual inspection of the 30-day averages of the innovations sequence (Figures 14-21) suggest the results are autocorrelated. This could be a result of structural errors in the model, as described above, or could be related to observation bias and error reported by McKenzie and Laenen (1998).

Results

For the Columbia River in Scenario1, the existing conditions, average annual duration of exceedance for the average simulated temperature increase from near zero at Wells Dam to somewhat greater than 0.06 at Priest Rapids. The influence of the Snake River leads to a doubling of the frequency of exceedance between Priest Rapids and McNary Dam. From McNary Dam to Bonneville the frequency increases only slightly. The range of the duration of exceedance, based on results from the simulated average plus one standard deviation and the simulated average minus one standard deviation, is of the order of ±0.04. The average magnitude of exceedances increases from 0.0 °C at Grand Coulee Dam to 1.4 °C at Bonnevill Dam.

With all dams removed (Scenario2), the average annual duration of exceedance estimated from the simulated average water temperatures is less than 0.05 at Bonneville Dam. The average magnitude of the exceedance also decreases to 0.6 °C .However, the range of the duration has increased such that the durations associated with the average simulation plus one standard deviation is approximately 0.08 greater than that of the average simulation. The duration associated with average simulation minus one standard deviation are only 0.04 less than that of the average simulation at Bonneville Dam. The increase in the range of the estimate for the river without dams is due to the increased response time associated with shallower depths and higher velocities. The duration of exceedance and exceedance magnitude properties for Scenario 3, for which tributary temperatures are constrained to be always less than 16 °C show little difference from that of Scenario 1, existing conditions.

In the Snake River, with dams in place (Figure 30), duration of exceedance is relatively high at the starting point (Snake R.M. 139.0), but nearly doubles between there and Ice Harbor Dam (Snake R.M. 9.0). Because the Snake is a smaller river, the range of the estimates is also greater than in the Columbia River. When the dams are removed (Figure 31), the analysis predicts that the mean duration of exceedance at Ice Harbor is approximately 63% of that when the dams are in place. The magnitude of exceedances in the Snake River for Scenario 1 increase from 1.0 °C at Lewiston to 1.8 °C at Ice Harbor. When dams are removed (Scenario 2), the average magnitude of exceedance remains the same at Lewiston, but decreases to 1.2 °C at Ice Harbor. As in the case of the main stem Columbia River, limiting the temperature of the tributaries has a negligible impact on either annual duration of exceedance or average magnitude of exceedance.

Conclusions

The results of the analysis lead to the following conclusions:

- The likelihood that both duration and magnitude with which water temperatures exceed the benchmark (20 °C) in the Columbia and Snake River main stems is greater with dams in place than with dams removed. The likelihood of these events remains essentially unchanged when existing conditions are modified such that tributary temperature are constrained to be equal to or less than 16 °C. That is, the model simulations predict that the impact of hydroelectric projects on water temperature in the main stem Columbia and Snake Rivers is greater than that of the major tributaries.

- The initial conditions for the Snake River at Lewiston, Idaho are such that the average annual duration with which water temperatures exceed the benchmark is approximately 0.11 (11% of the year) and the average magnitude of the xceedance is approximately 1 °C.

- With dams in place,the Snake River increases the average annual duration of exceedance in the Columbia River at the confluence from 0.06 (6%) to 0.11 (11%). With dams removed, the corresponding increase is from less than 0.01 (1%) to nearly 0.03 (3%).

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Table 1. Mean annual discharges at selected sites on the main stem Columbia and Snake Rivers

Station Name	Gage #	Station Location		Period of Record	Average Flow
		Latitude	Longitude		
Snake River near Anatone	13334300	46° 05'50"	116° 58'36"	1958-1995	34814
Snake River below Ice Harbor Dam	13353000	46°15'02"	118° 52'55"	1913-1992	53377
Columbia River at the International Boundary	12399500	49° 00'03"	117° 37'42"	1938-1994	99214
Columbia River at Grand Coulee	12436500	47° 57'56"	118° 58'54"	1923-1994	108187
Columbia River at Bridgebport	12438000	48° 00'24"	119° 39'51"	1952-1993	110170
Columbia River below Wells Dam	12450700	47° 56'48"	119° 51'56"	1968-1994	109357
Columbia River at Rocky Reach Dam	12453700	47° 31'28"	120° 18'04"	1961-1994	113185
Columbia River below Rock Island Dam	12462600	47° 19'57"	120° 04'48"	1961-1994	116271
Columbia River below Priest Rapids Dam	12472800	46° 37'44"	119° 51'49"	1918-1994	118377
Columbia River at the Dalles	14105700	45° 36'27"	121° 10'20"	1878-1995	191021

Table 2. Hydroelectric projects on the mainstem Columbia and Snake Rivers

Project	River Mile	Start of Operation	Generating Capacity (megawatts)	Storage Capacity (1000's acre-feet)
Grand Coulee	596.6	1942	6,494	8,290
Chief Joseph	545.1	1961	2.069	588
Wells	515.8	1967	774	281
Rocky Reach	473.7	1961	1,347	440
Rock Island	453.4	1933	622	132
Wanapum	415.8	1963	1,038	710
Priest Rapids	397.1	1961	907	231
McNary	292.0	1957	980	1,295
John Day	215.6	1971	2,160	2,294
The Dalles	191.5	1960	1,780	311
Bonneville	146.1	1938	1,050	761
Lower Granite	107.5	1975	810	474
Little Goose	70.3	1970	810	541
Lower Monumental	41.6	1969	810	351
Ice Harbor	9.7	1962	603	400

Table 3. Parameter list for water quality limited segments of the Columbia and Snake River in Washington.

WRIA	Water Name	Segment ID	Parameter	Action Needed
31	Columbia River	NN57SG	Temperature	TMDL
31	Columbia River	NN57SG	Sediment Bioassay	Other Control
31	Columbia River	NN57SG	Total Dissolved Gas	TMDL
33	Snake River	YB36JO	Total Dissolved Gas	TMDL
33	Snake River	YB36JO	Temperature	TMDL
33	Snake River	YB36JO	Dissolved Oxygen	None
35	Snake River	YB36JO	Temperature	TMDL
35	Snake River	YB36JO	Total Dissolved Gas	TMDL
40	Columbia River	NN57SG	Total Dissolved Gas	TMDL
41	Columbia River	NN57SG	Total Dissolved Gas	TMDL
45	Columbia River	NN57SG	Total Dissolved Gas	TMDL
45	Columbia River	NN57SG	Water Column Bioassay	Other Control
47	Columbia River	NN57SG	Total Dissolved Gas	TMDL
47	Columbia River	NN57SG	Temperature	TMDL
50	Columbia River	NN57SG	Total Dissolved Gas	TMDL
53	Columbia River	NN57SG	Total Dissolved Gas	TMDL
58	Franklin D Roosevelt Lake	NN57SG	Sediment Bioassay	Other Control
58	Franklin D Roosevelt Lake	NN57SG	Total Dissolved Gas	TMDL
58	Franklin D Roosevelt Lake	NN57SG	Mercury	TMDL
61	Franklin D Roosevelt Lake	NN57SG	Total Dissolved Gas	TMDL
61	Franklin D Roosevelt Lake	NN57SG	Arsenic	TMDL
61	Franklin D Roosevelt Lake	NN57SG	Sediment Bioassay	Other Control
61	Franklin D Roosevelt Lake	NN57SG	Temperature	TMDL
61	Franklin D Roosevelt Lake	NN57SG	Dissolved Oxygen	TMDL

Table 4. U.S. Geological Survey gaging stations for major tributaries of the Columbia and Snake Rivers in the study area

Station Name	Agency	Station Number	Station Location		Period of Record
			Latitude	Longitude	
Clearwater River at Spalding	US Geological Survey	13342500	46°26'55"	116°49'35"	1911-1996
Tucannon River at Powers	Washington DOE	35B060	46°32'18"	118°09'18"	10/17/73 – 09/02/96
Palouse River at Hooper	Washington DOE	34A070	46°45'33"	118°08'49"	07/30/59 – 09/02/96
Okanogan River at Malott	Washington DOE	49A070	48°16'53"	119°42'12"	11/17/66 – 09/10/96
Methow River at Pateros	Washington DOE	48A070	48°04'29"	119°57'20"	07/29/59 – 09/10/96
Chelan River at Chelan	Washington DOE	47A070	47°50'23"	120°01'11"	07/20/60 – 09/14/94
Crab Creek near Beverly	Washington DOE	41A070	47°11'23"	119°15'54"	10/24/61 – 09/05/94
			46°39'20"	46°39'20"	
Yakima River at Kiona	Washington DOE	37A090	46°15'13"	119°28'37"	03/20/68 – 09/09/96
John Day River at Highway 206	Oregon DEQ	404065	45°28'37"	120°28'07"	02/11/73 – 12/04/97
Deschutes River at Deschutes Park	Oregon DEQ	402081	45°37'40"	120°54'13"	07/16/62 – 12/01/97

Table 5. Sources of data for developing the hydraulic characteristics of the Columbia and Snake Rivers.

River Segment	Data Source
Columbia River: Grand Coulee Dam to Confluence with the Snake River	Columbia River Thermal Effects cross-sectional data (Yearsley)
Snake River: Lewiston, Idaho to Confluence with the Columbia River	US Army Corps of Engineers (Walla Walla District) HEC-6 cross-sectional data
Columbia River: Confluence with the Snake River to Bonneville Dam	NOAA Navigation Charts

Table 6. U.S. Geological Survey gaging stations for the main stem Columbia and Snake Rivers and their major tributaries in the study area

Station Name	Station Number	Station Location		Period of Record	Drainage Area (sq. miles)	Gage Datum (feet above MSL)
		Latitude	Longitude			
Snake River at Anatone	13334300	46°05'50"	116°58'36"	1958-1995	92960	807.
Clearwater River at Spalding	13342500	46°26'55"	116°49'35"	1911-1996	9570	4360.
Tucannon River near Starbuck	13344500	46°39'20"	118°03'55"	1915-1992	431	730.
Palouse River at Hooper	13351999	46°45'31"	118°05'52"	1898-1994	2500	1041.
Columbia River at Grand Coulee	12436500	47°57'56"	118°58'54"	1923-1995	74700	900.
Okanogan River at Malott	12445000	48°37'57"	119°42'12"	1966-1994	8080	784.
Methow River at Pateros	12449950	48°04'39"	119°59'02"	1959-1994	1772	900.
Chelan River at Chelan	12452500	47°50'05"	120°00'43"	1904-1993	924	-----
Crab Creek near Beverly	12472600	46°49'48"	119°49'48"	1951-1994	4840	500.
Yakima River at Kiona	12510500	46°15'13"	119°28'37"	1906-1994	5615	454.
John Day River at McDonald Ferry	14048000	45°35'16"	120°24'30"	1905-1994	7580	392.
Deschutes River at Moody	14103000	45°37'20"	120°54'05"	1898-1994	10500	168.

Table 7. First-order meteorological stations used to estimate heat budget parameters for the Columbia and Snake Rivers.

Station Name	WBAN #	Period of Record	Latitude	Longitude	Station Elev (feet abv MSL)
Lewiston, Idaho	24149	01/01/1948-12/31/1997	46°23'00"	117°01'00"	1436
Pendleton, Oregon	24155	01/01/1948-12/31/1997	45°41'00"	118°51'00"	1482
Spokane, Washington	24157	01/01/1948-12/31/1997	47°38'00"	117°32'00"	2356
Yakima, Washington	24243	01/01/1948-12/31/1997	46°34'00"	120°23'00"	1064

Table 8. Weather stations from the Local Climatological Data base included in the parameter estimation process for heat budget calculations

Station Name	Station #	Latitude	Longitude	Station Elevation	Period of Record
Connell	1690	46° 45'37	117°10'10"	1020.	11/01/1960 – 12/31/1997
Coulee Dam	1767	47° 57'00	119°00'00"	1700.	06/01/1948 – 12/31/1997
The Dalles	8407	45° 36'00"	121°12'00"	102	07/01/1948 – 12/31/1997
Pullman	6789	46° 45'37"	117°10'10"	2545	10/21/1940 – 12/31/1997
Richland	7015	46° 23'00"	117°01'00"	373	06/01/1948 – 12/31/1997
Wenatchee	9074	47° 25'00"	120°19'00"	640	02/08/1877 – 12/31/1997

Table 9. Parameters for estimating input temperatures of main stem and tributaries using nonlinear regression methods described by Mohseni et al (1999)

River	Weather Station	Week for Rising Limb / Week for Falling Limb	T_{max}	β	γ	μ
Chelan River	Wenatchee	1	27	13.4139	0.1857	0.5159
		30	27	8.6005	0.1191	0.3308
Crab Creek	Wenatchee	1	27	11.7496	0.1627	0.4519
		30	27	11.9758	0.1658	0.4606
Deschutes River	Yakima	1	25	11.0004	0.1523	0.4231
		30	25	8.2957	0.1149	0.3191
J ohn Day River	Lewiston	1	30	13	0.18	0.5
		32	30	12.2061	0.169	0.4695
Okanogan River	Wenatchee	1	28	16.3357	0.2262	0.6283
		30	28	14.1825	0.1964	0.5455
Palouse River	Yakima	1	30	14.0793	0.1949	0.5415
		30	30	14.3647	0.1989	0.5525
Tucannon River	Lewiston	1	24	13	0.18	0.5
		32	24	12.3365	0.1708	0.4745
Wenatchee River	Wenatchee	1	25	17.8776	0.2475	0.6876
		30	25	13.4335	0.186	0.5167
Yakima River	Yakima	1	28	12.7321	0.1763	0.4897
		30	28	11.9158	0.165	0.4583

Table 10. Final configuration of weather stations used to estimate the heat budget terms for the mathematical model of water temperature in the Columbia and Snake Rivers.

Weather Station	Station Type	River Segments
Lewiston, Idaho	SAMSON	Snake River from Lewiston, Idaho to the Confluence with the Columbia
Wenatchee, Washington	LCD	Columbia River from Grand Coulee Dam to Rock Island Dam
Yakima, Washington	SAMSON	Columbia River from Rock Island Dam to the Confluence with the Snake
Richland, Washington	LCD	Columbia River from the confluence with the Snake to Bonneville Dam

Table 11. Measurement bias, measurement error variance and systems dynamic error variance at locations of scroll case temperature measurements on the Columbia and Snake Rivers.

Location of Measurement	Measurement Bias (^{o}c)	Error Variance	
		Measurement $^{o}c^{2}$	Systems Dynamics $^{o}c^{2}$
Lower Granite Dam	0.0	0.50	0.008
Little Goose Dam	0.0	0.50	0.008
Lower Monumental Dam	0.0	0.50	0.008
Ice Harbor Dam	0.0	0.5	0.008
Rock Island Dam	0.5	0.50	0.008
Priest Rapids Dam	0.0	0.50	0.008
McNary Dam	1.0	0.50	0.008
The Dalles Dam	1.0	0.50	0.008
Bonneville Dam	1.5	0.50	0.008

Figure 6. Simulated and observed water temperatures at Bonneville Dam for the period 1990-1995

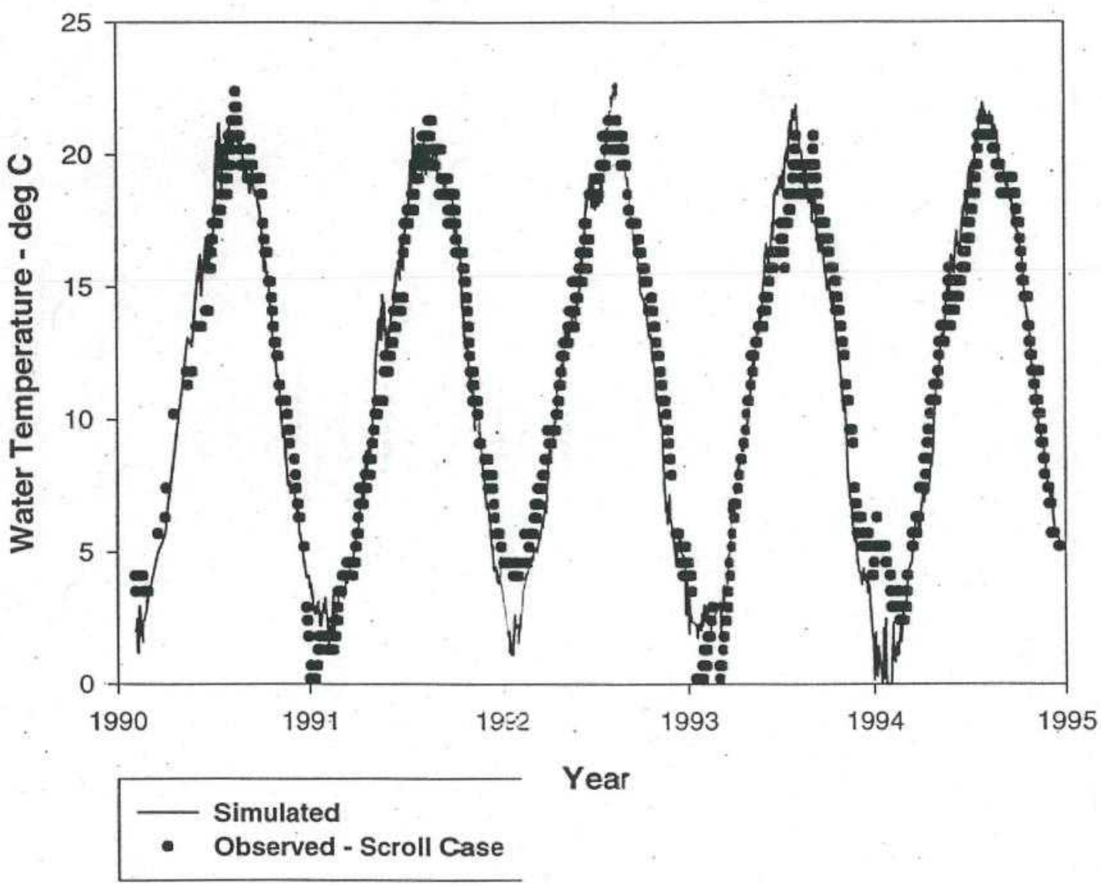


Figure 7. Simulated and observed water temperatures at John Day Dam for the period 1990-1995

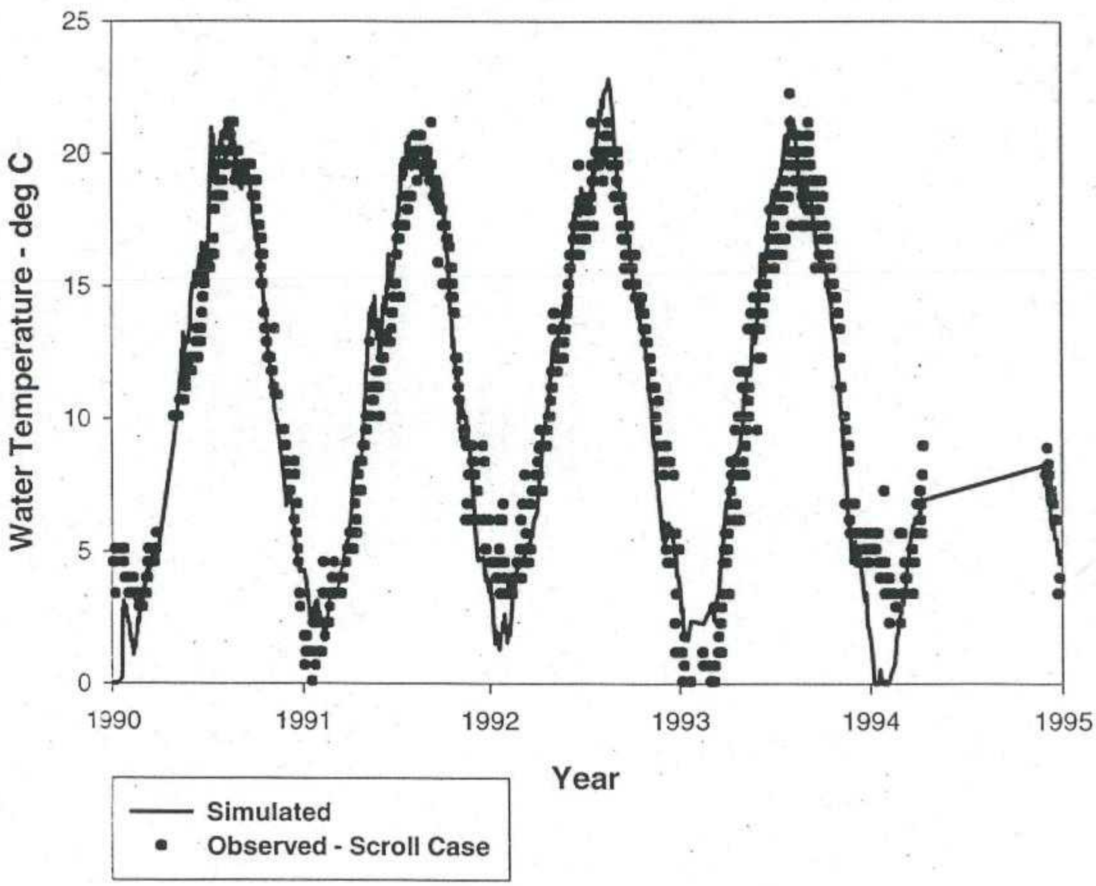


Figure 8. Simulated and observed water temperatures at McNary Dam for the period 1990-1995

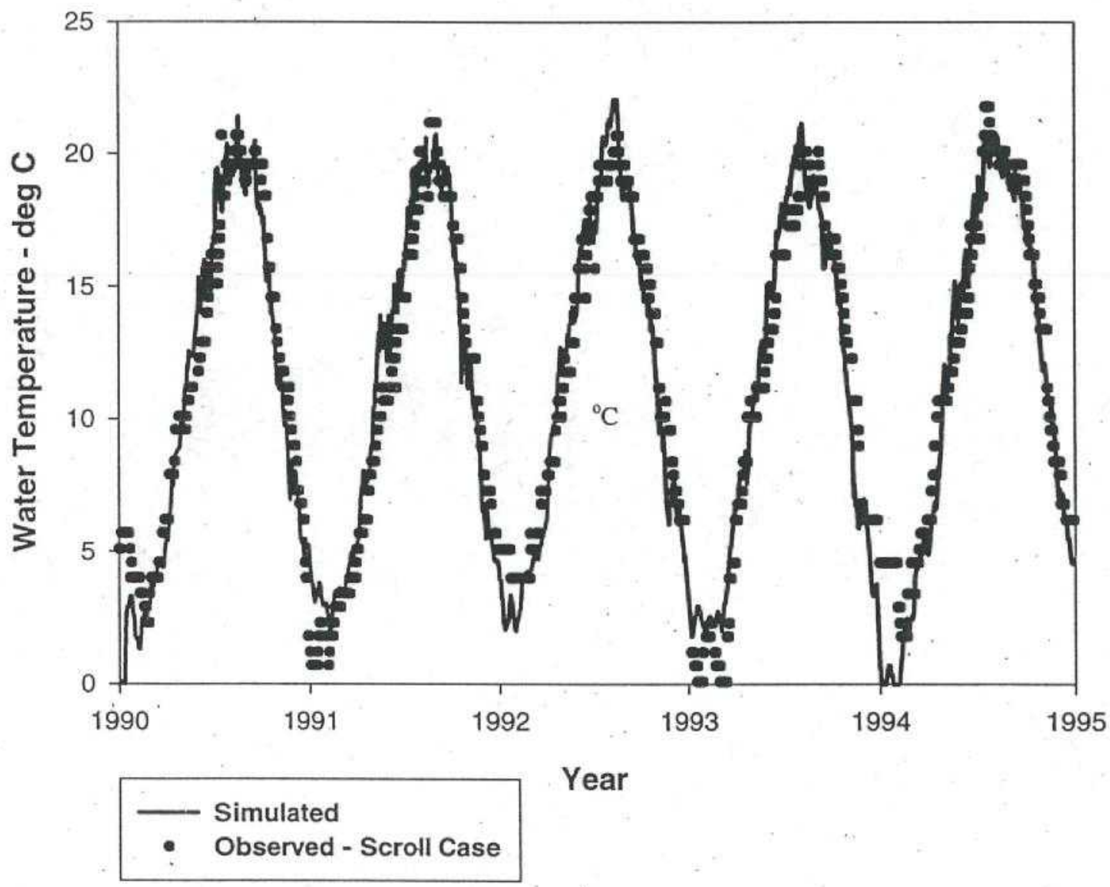


Figure 9. Simulated and observed water temperatures at Priest Rapids Dam for the period 1990-1995

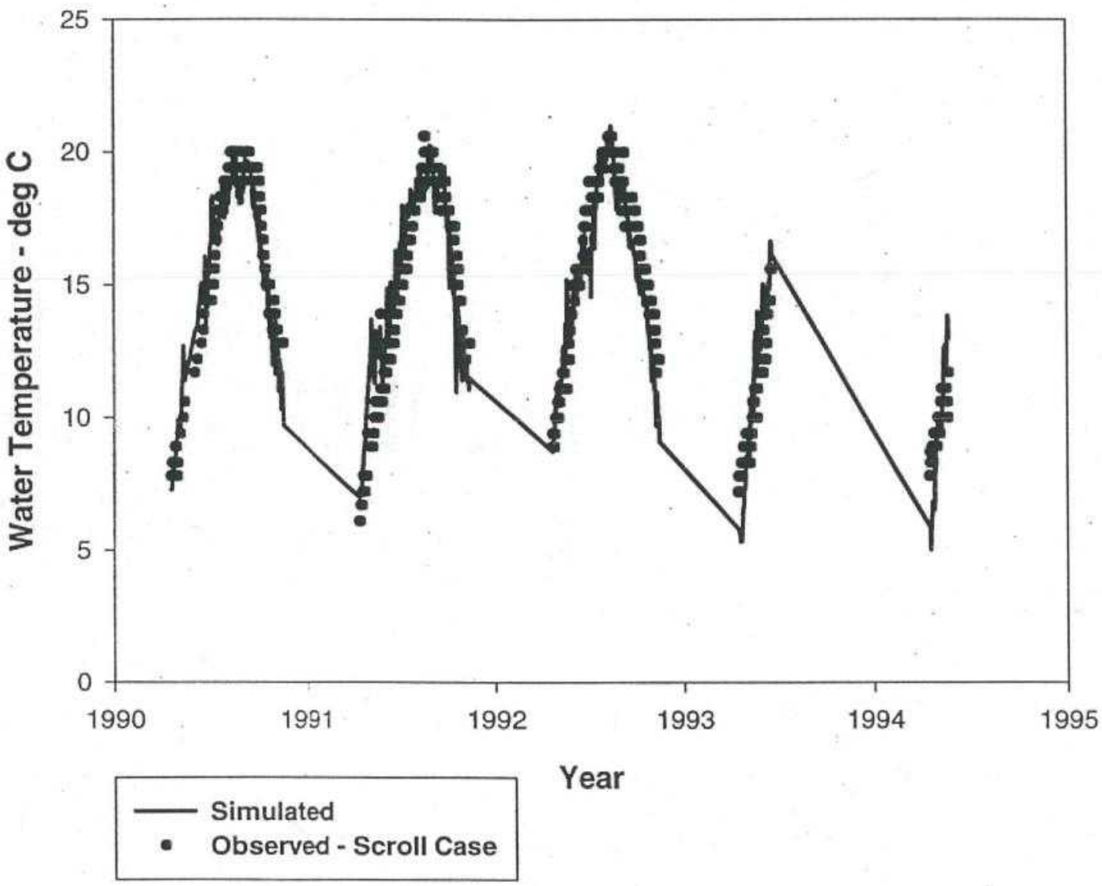


Figure 10. Simulated and observed water temperatures at Rock Island Dam for the period 1990-1995.

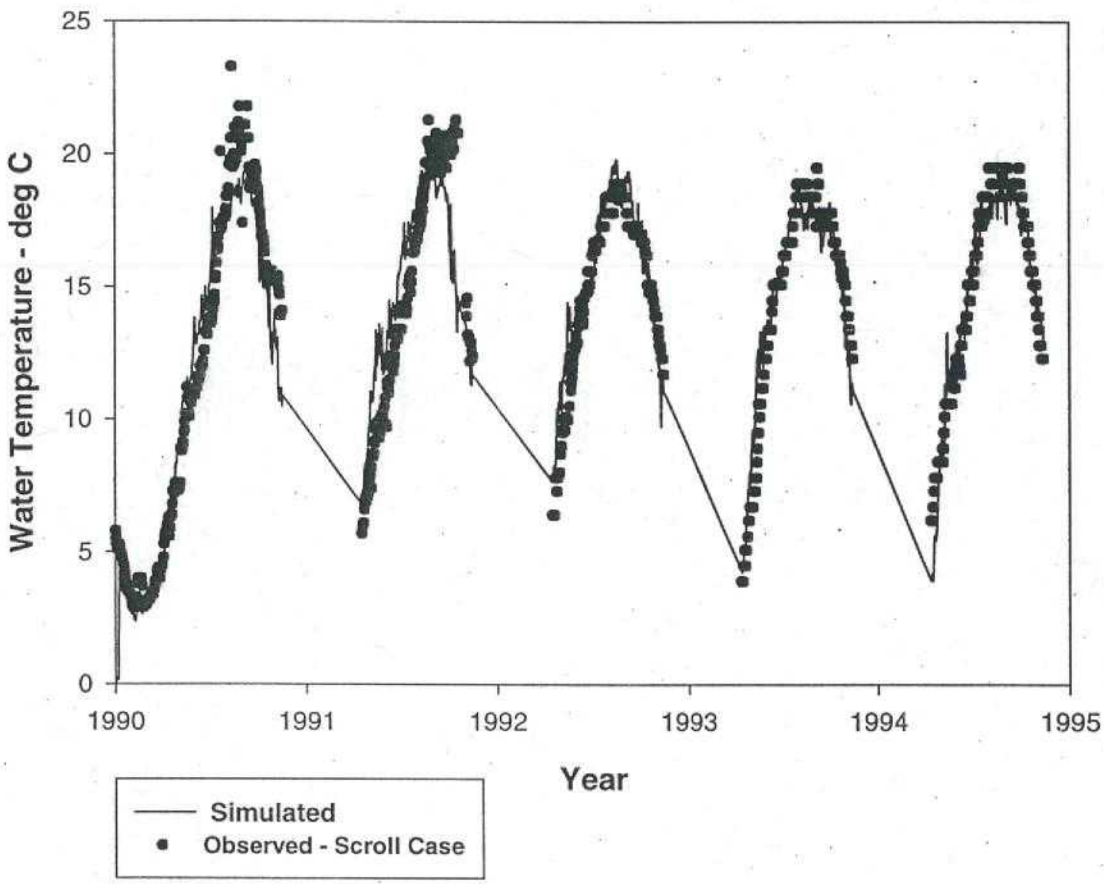


Figure 11. Simulated and observed water temperatures at Ice Harbor Dam for the period 1990-1995

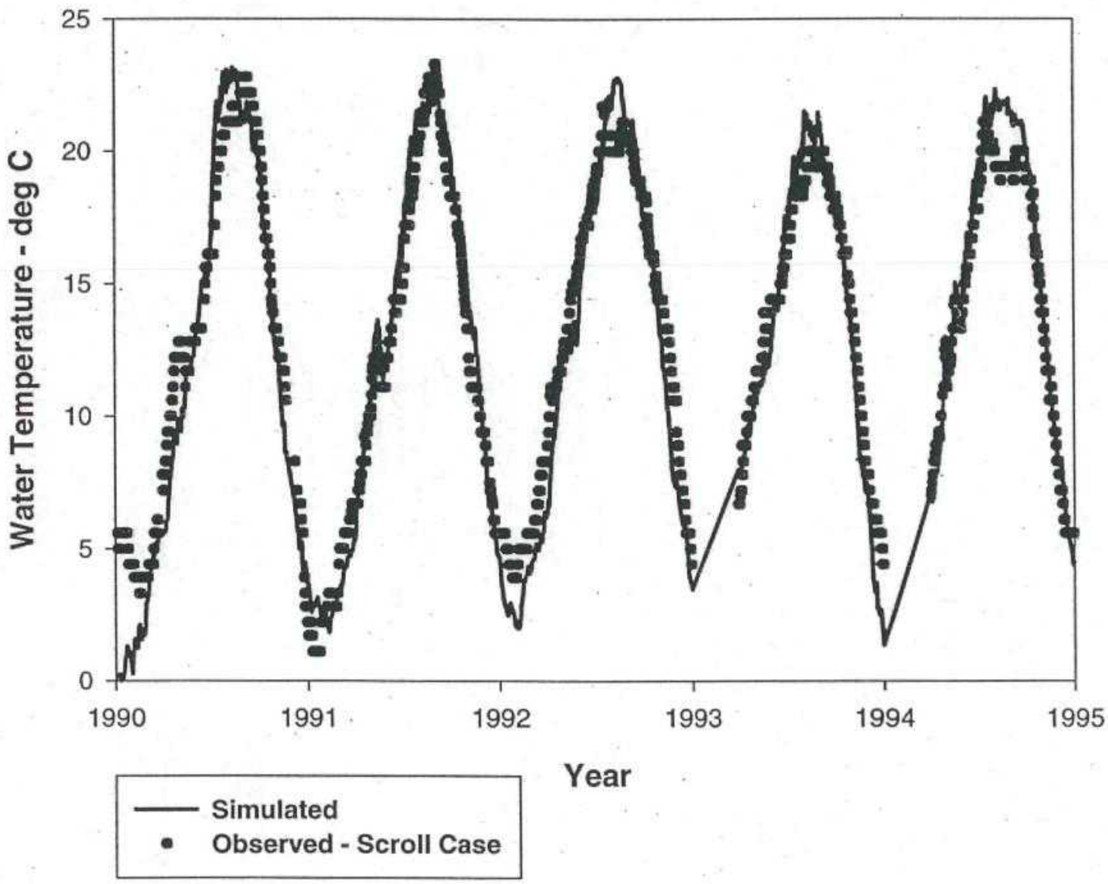


Figure 12. Simulated and observed water temperatures at Lower Monumental Dam for the period 1990-1995.

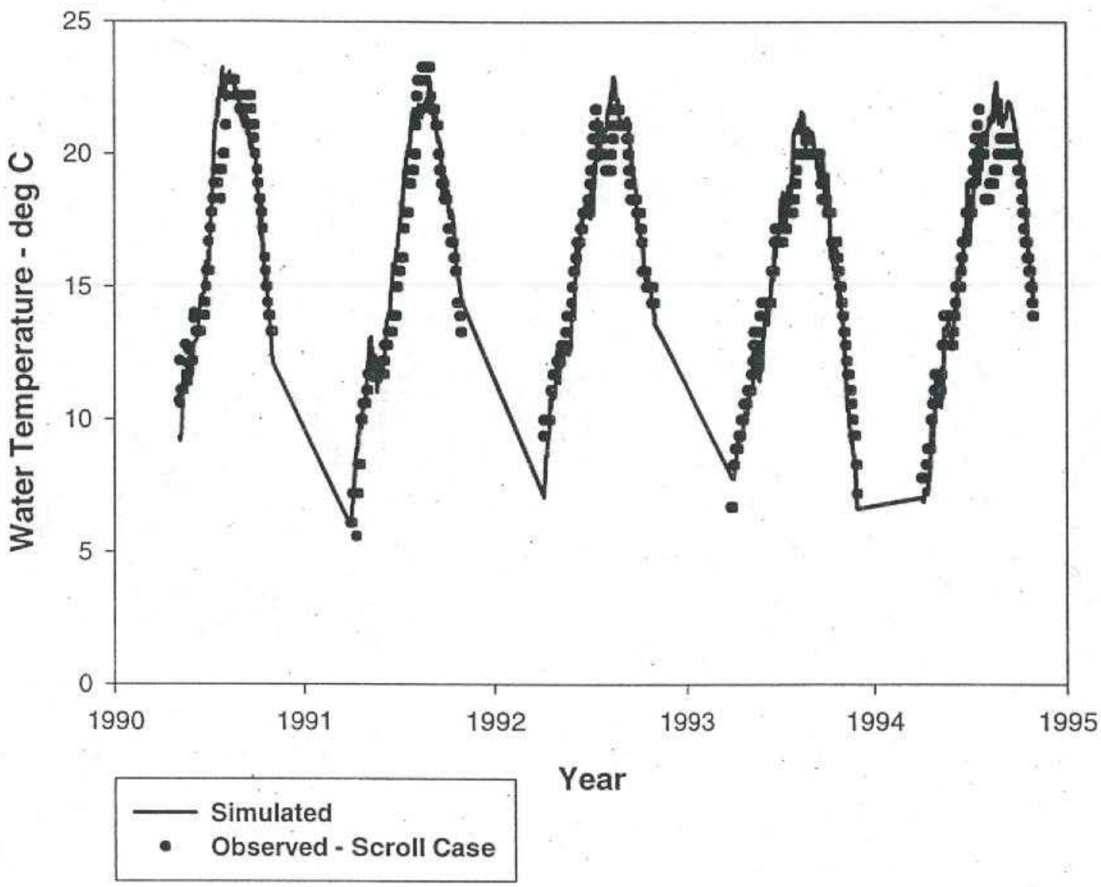


Figure 13. Simulated and observed water temperatures at Lower Granite Dam for the period 1990-1995.

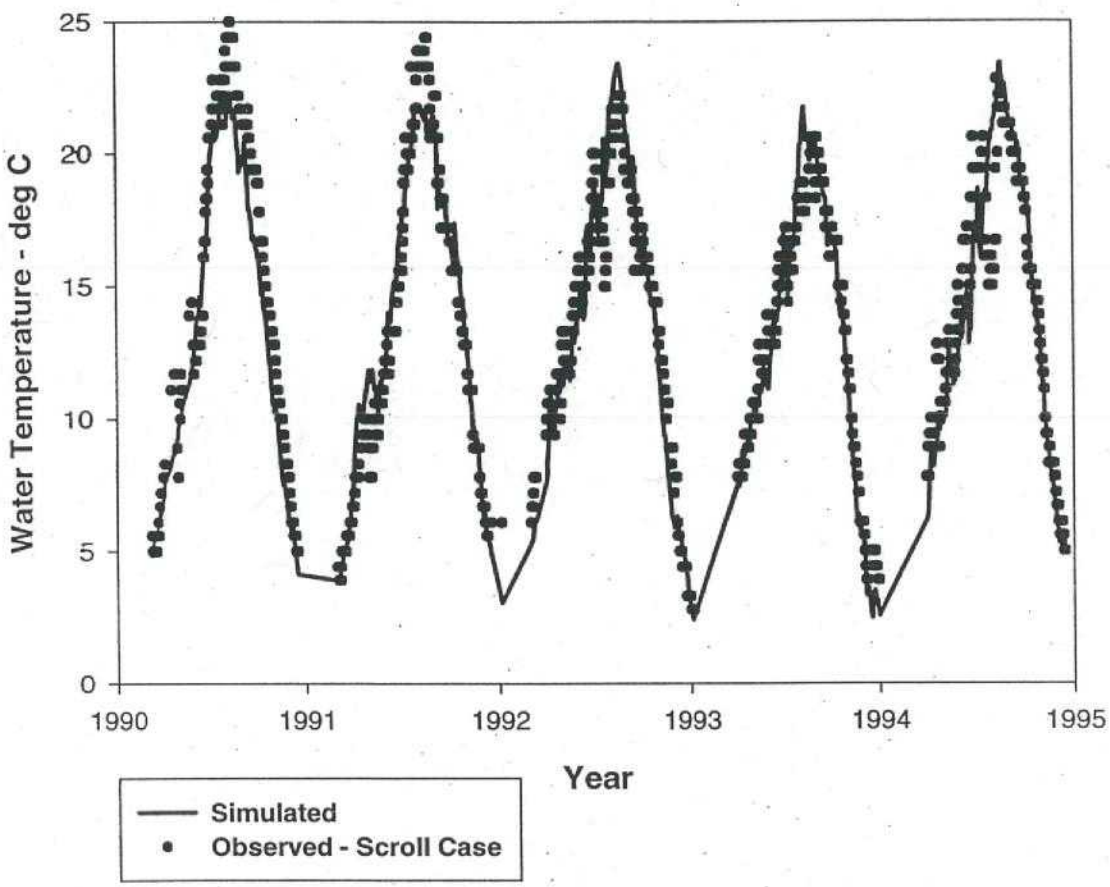


Figure 14. 30-day moving average of innovations sequence at Bonneville Dam for the period 1990-1995.

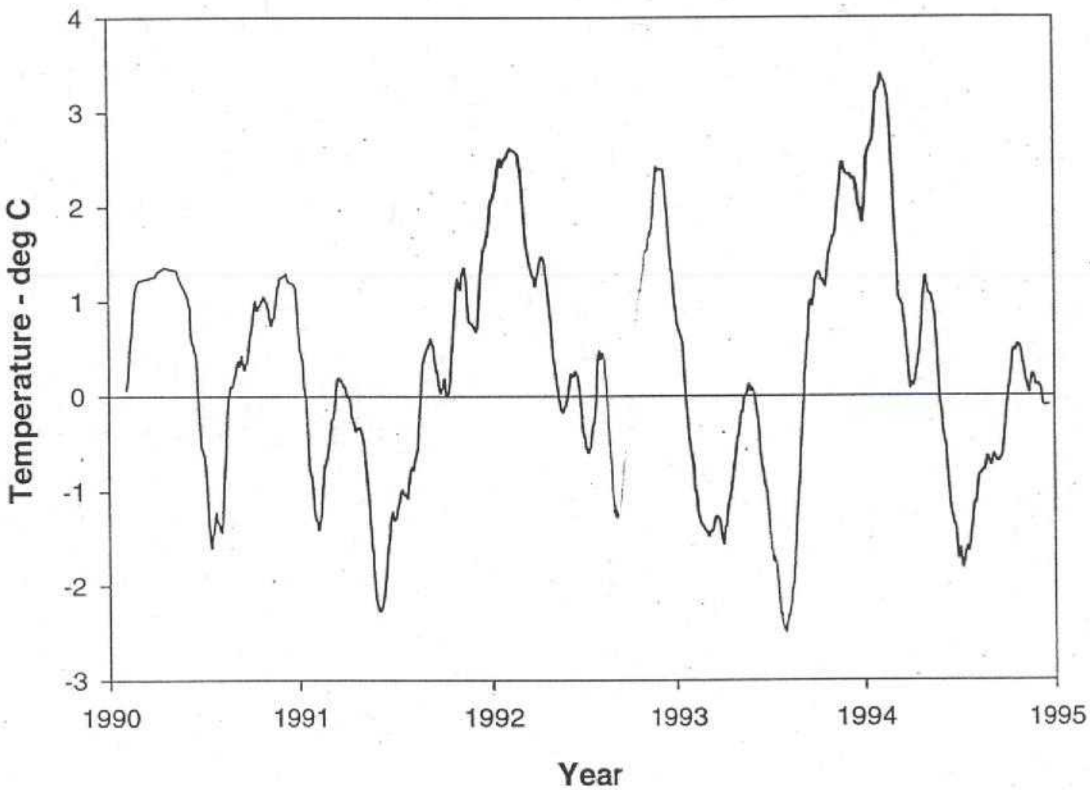


Figure 15. 30-day moving average of innovations sequence at John Day Dam for the period 1990-1995.

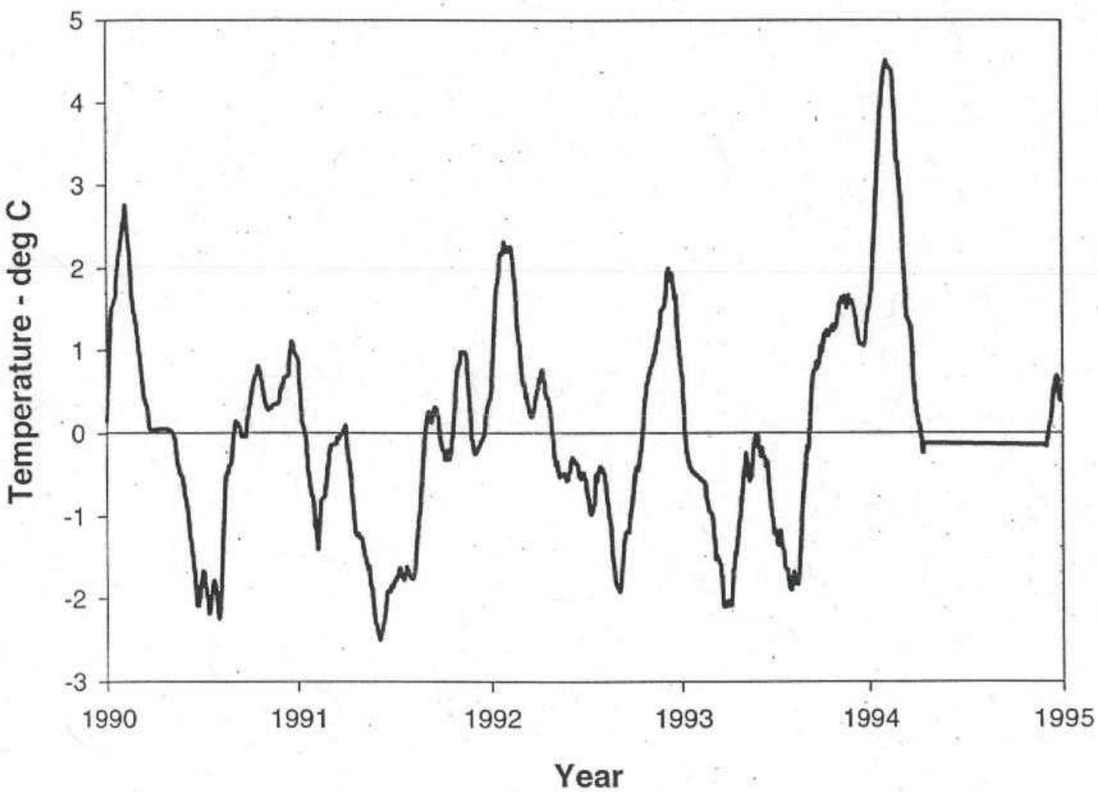


Figure 16. 30-day moving average of innovations sequence at McNary Dam for the period 1990-1995.

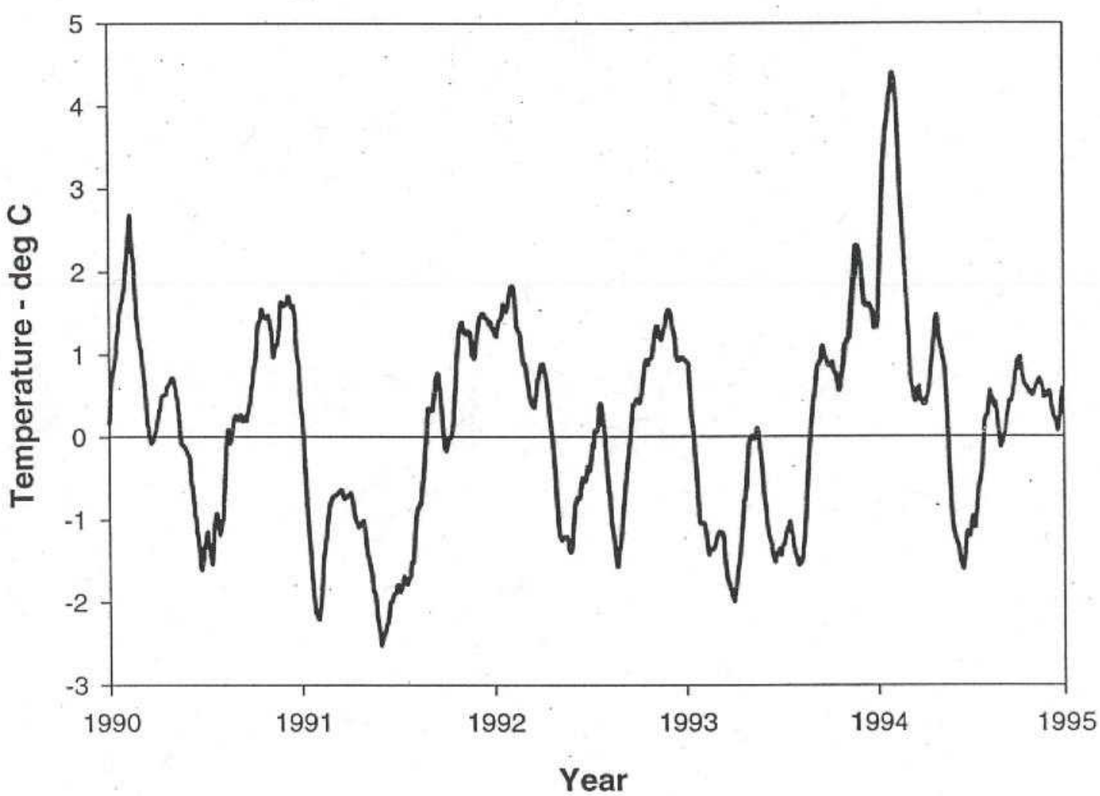


Figure 17. 30-day moving average of innovations sequence at Priest Rapids Dam for the period 1990-1995.

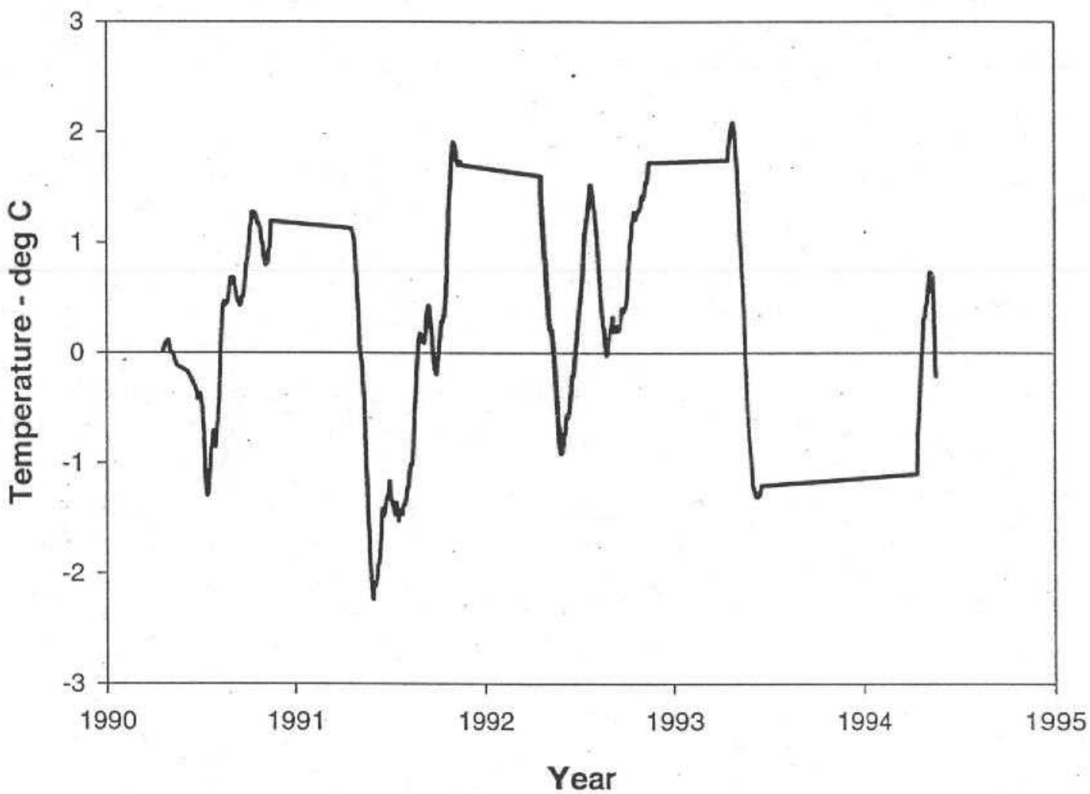


Figure 18. 30-day moving average of innovations sequence at Rock Island Dam for the period 1990-1995.

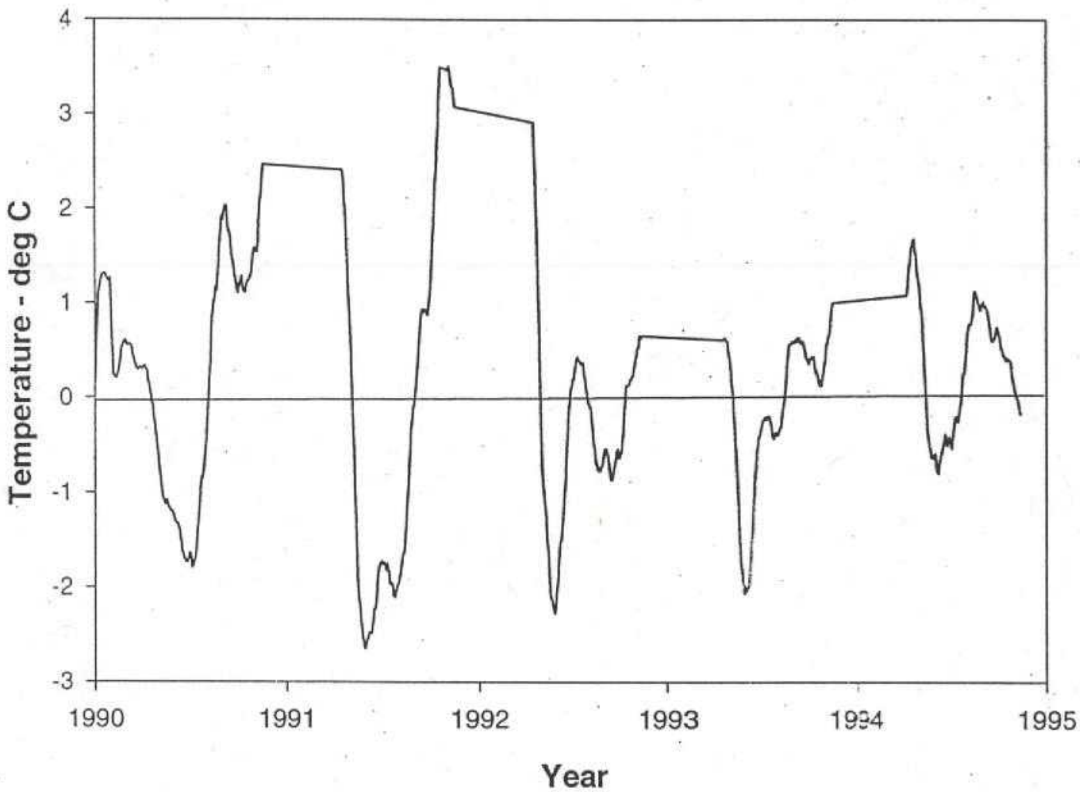


Figure 19. 30-day moving average of innovations sequence at Ice Harbor Dam for the period 1990-1995.

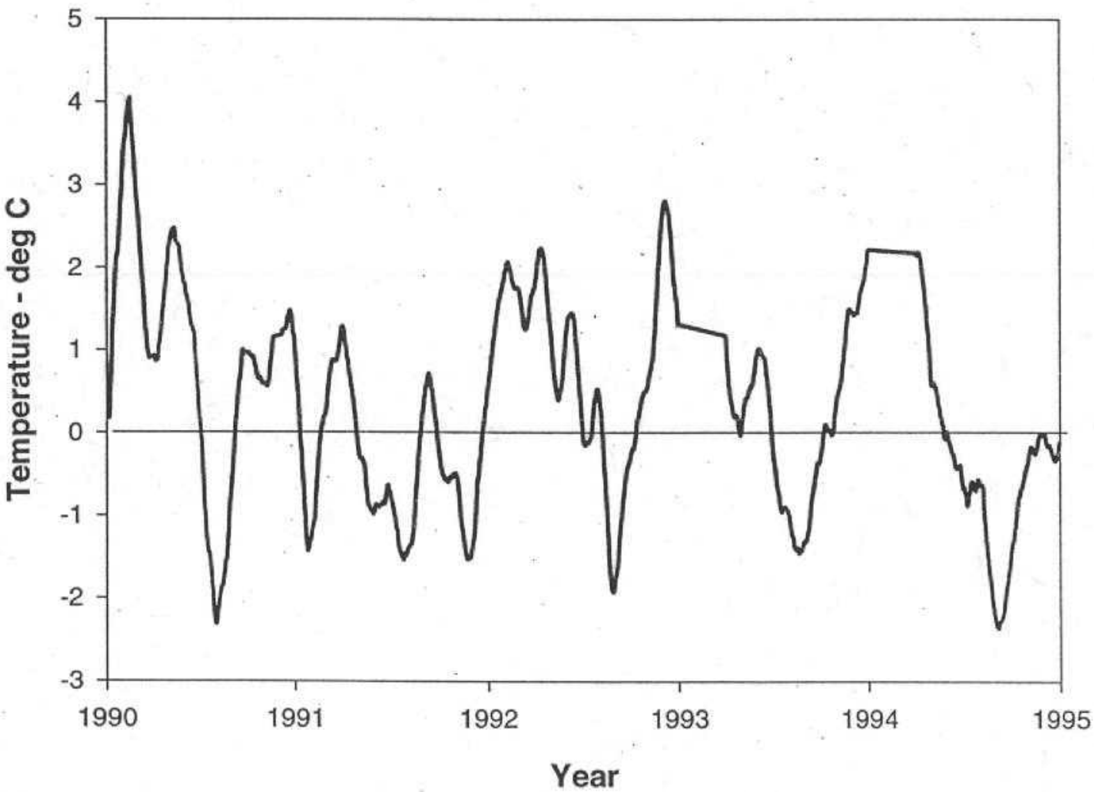


Figure 20. 30-day moving average of innovations sequence at Lower Monumental Dam for the period 1990-1995.

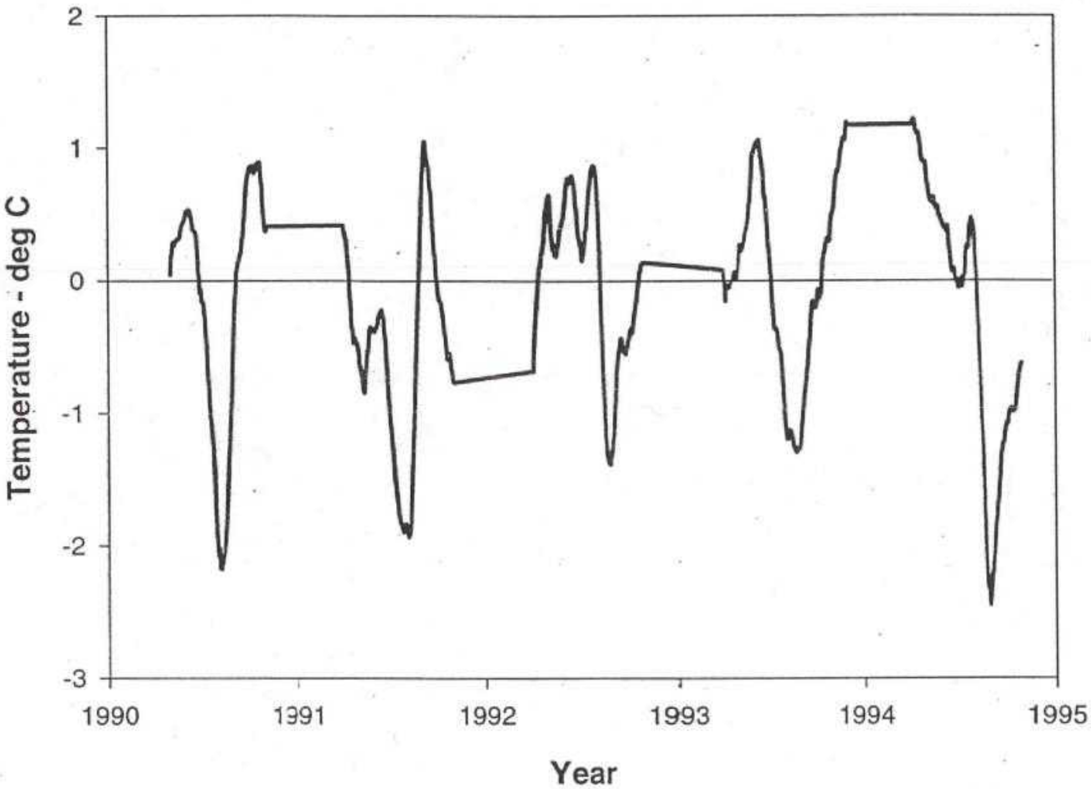


Figure 21. 30-day moving average of innovations sequence at Lower Granite Dam for the period 1990-1995.

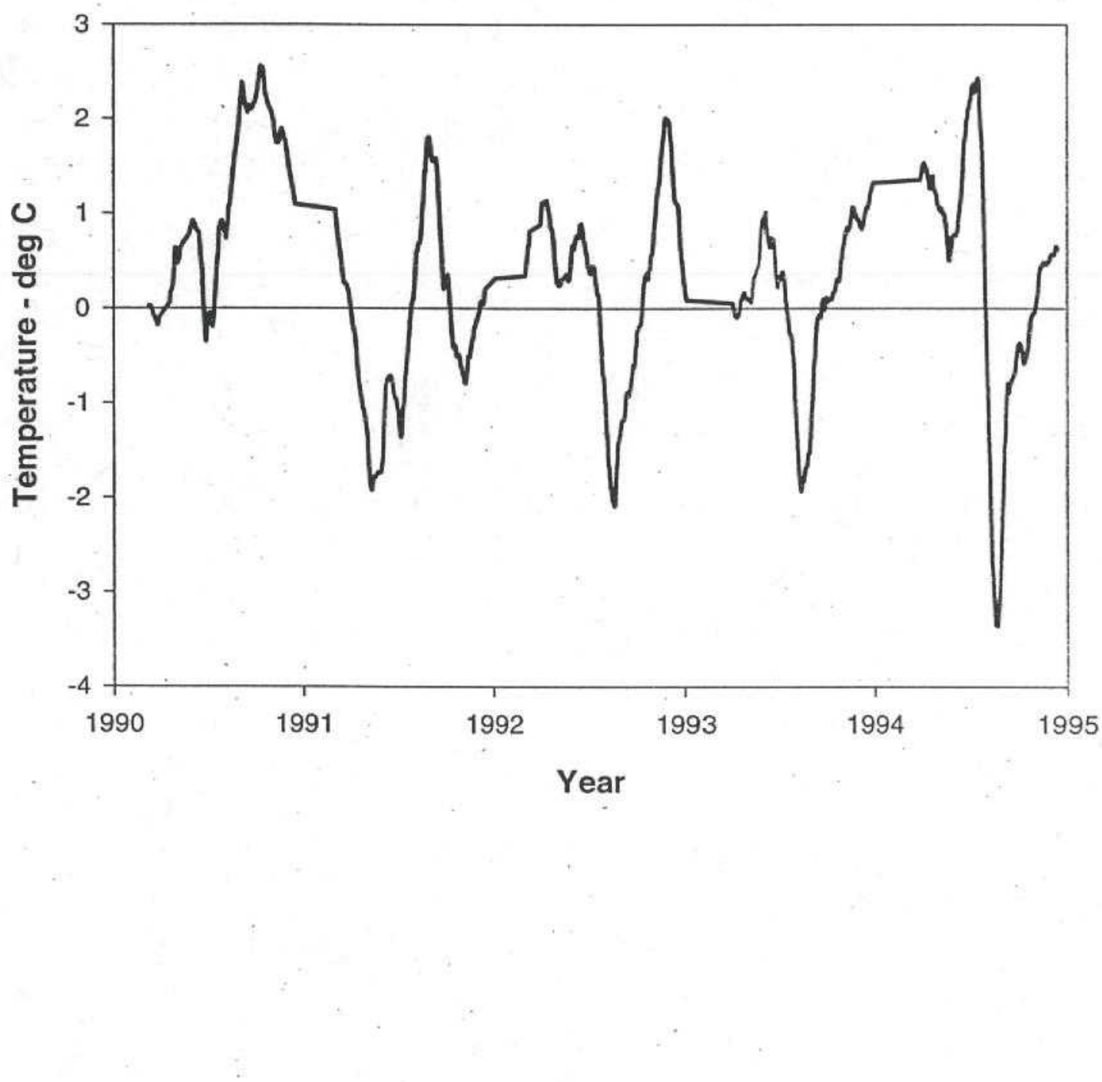


Figure 22. Actual and simulated innovations variance at Bonneville Dam for the period 1990-1995.

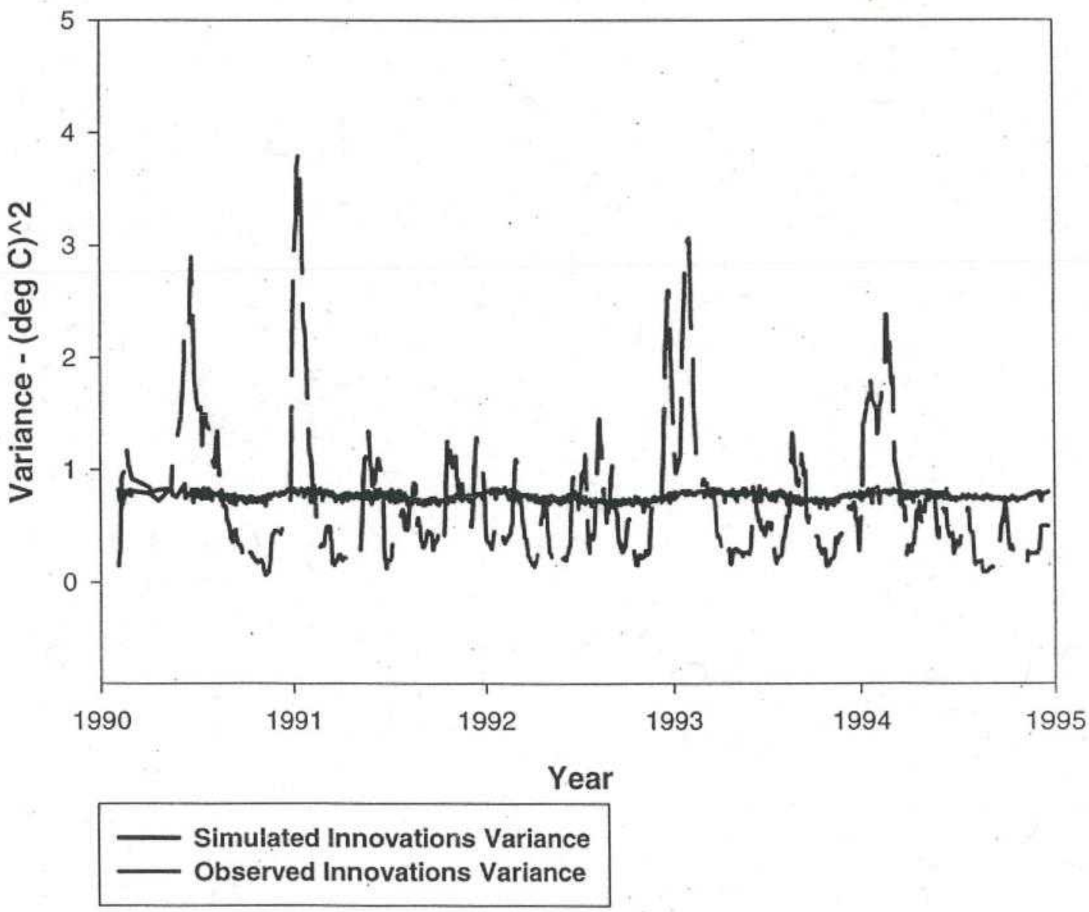


Figure 23. Actual and simulated innovations variance at John Day Dam for the period 1990-1995.

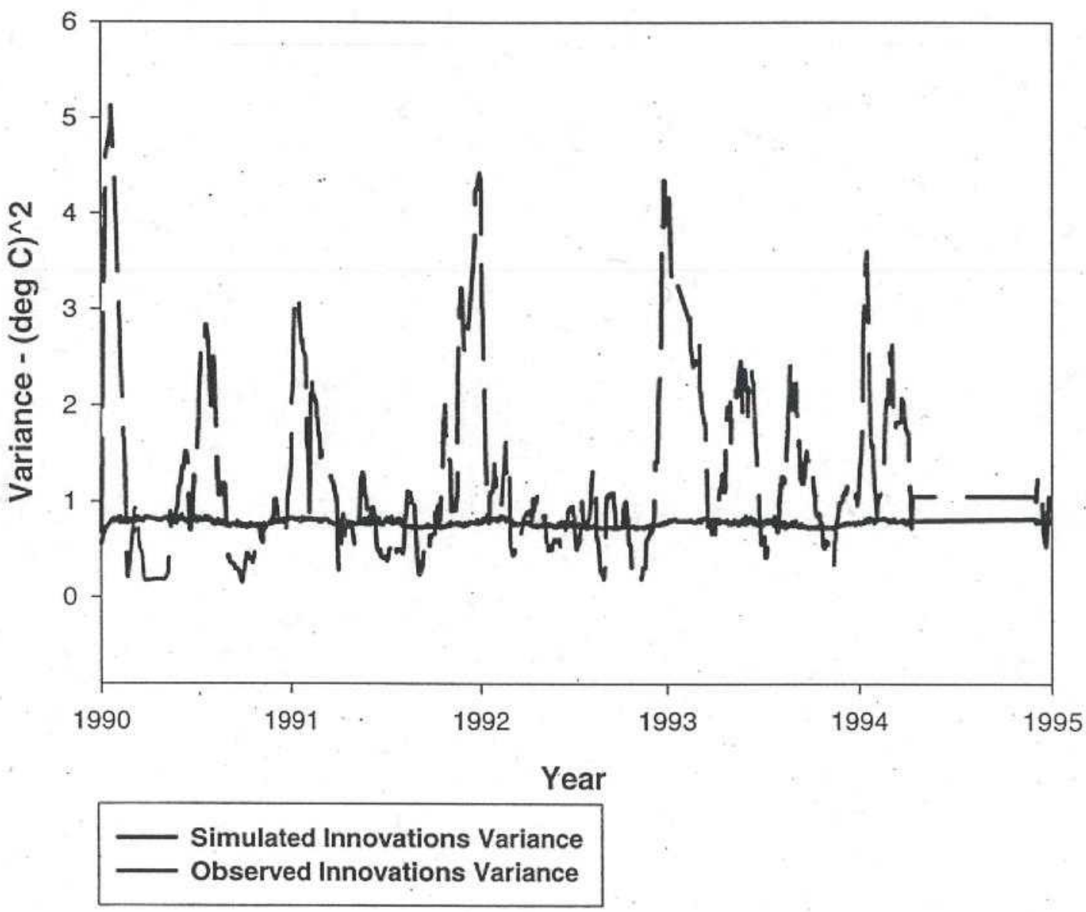


Figure 24. Actual and simulated innovations variance at McNary Dam for the period 1990-1995.

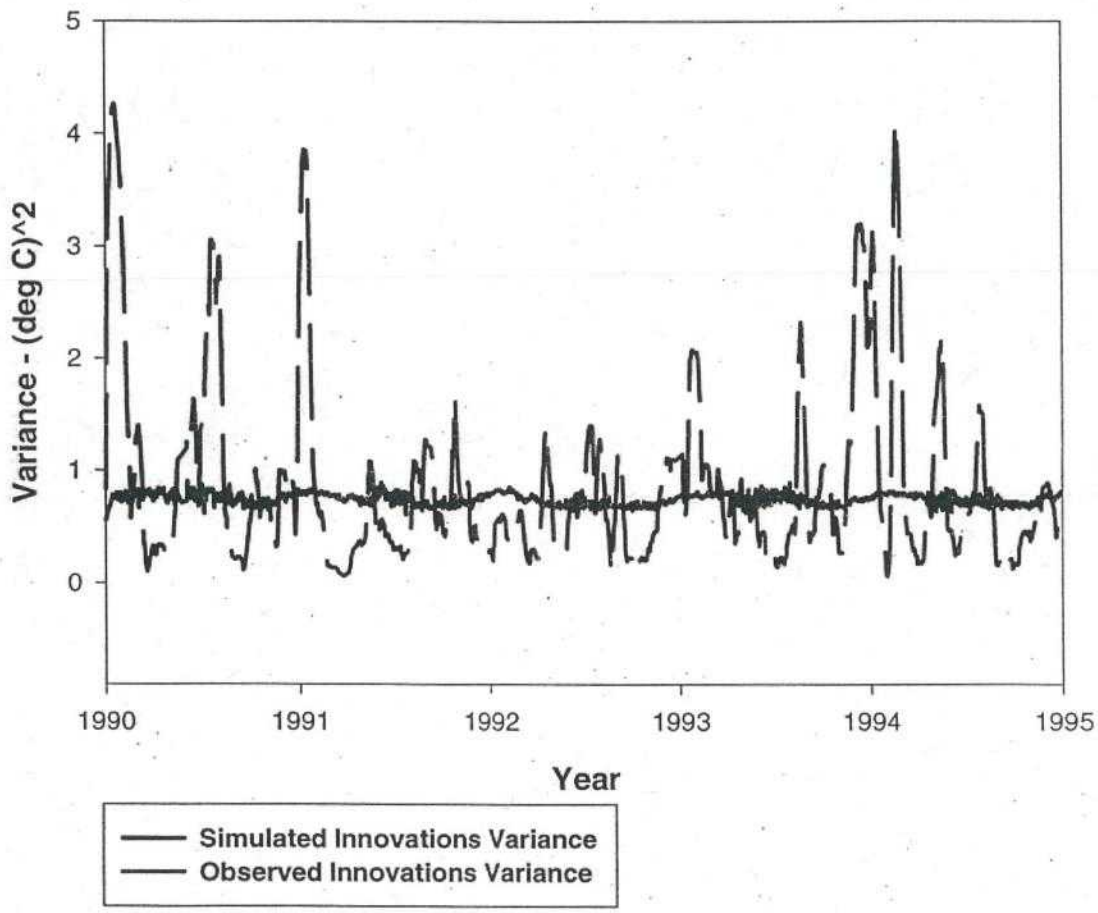


Figure 25. Actual and simulated innovations variance at Priest Rapids Dam for the period 1990-1995.

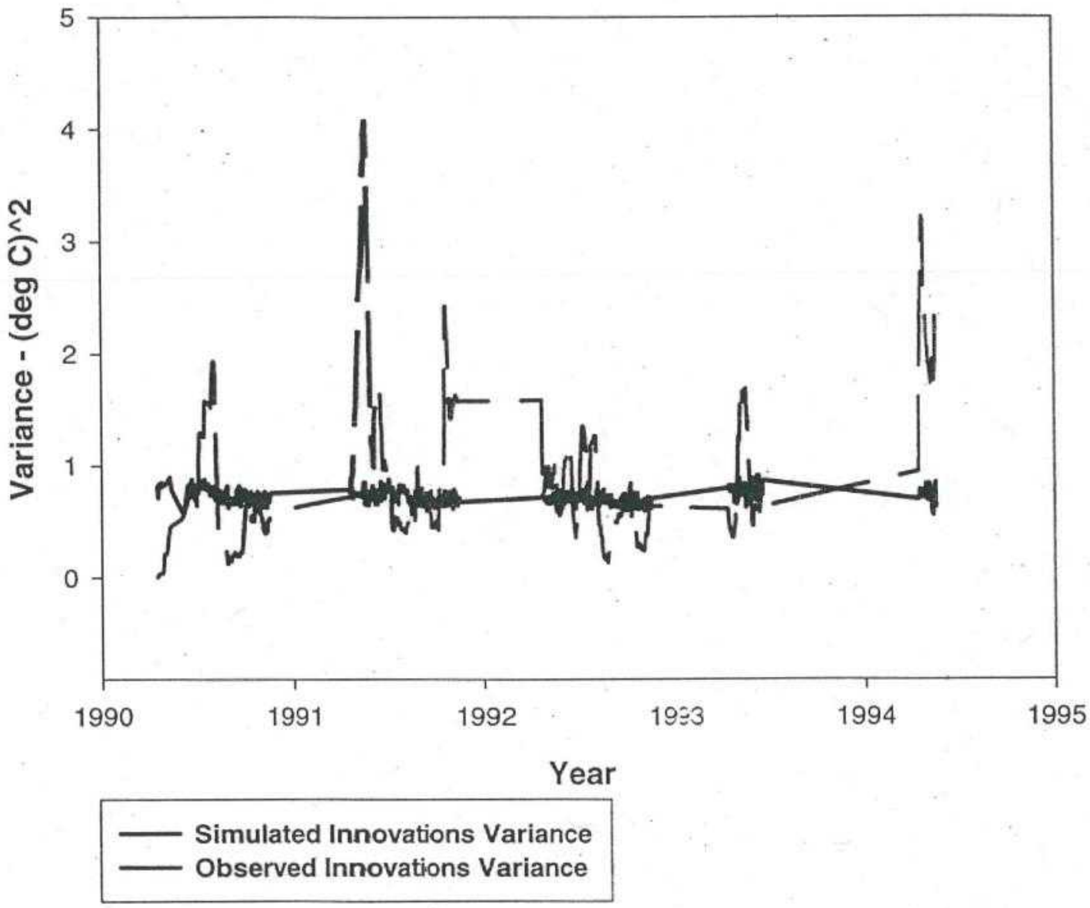


Figure 26. Actual and simulated innovations variance at Rock Island Dam for the period 1990-1995

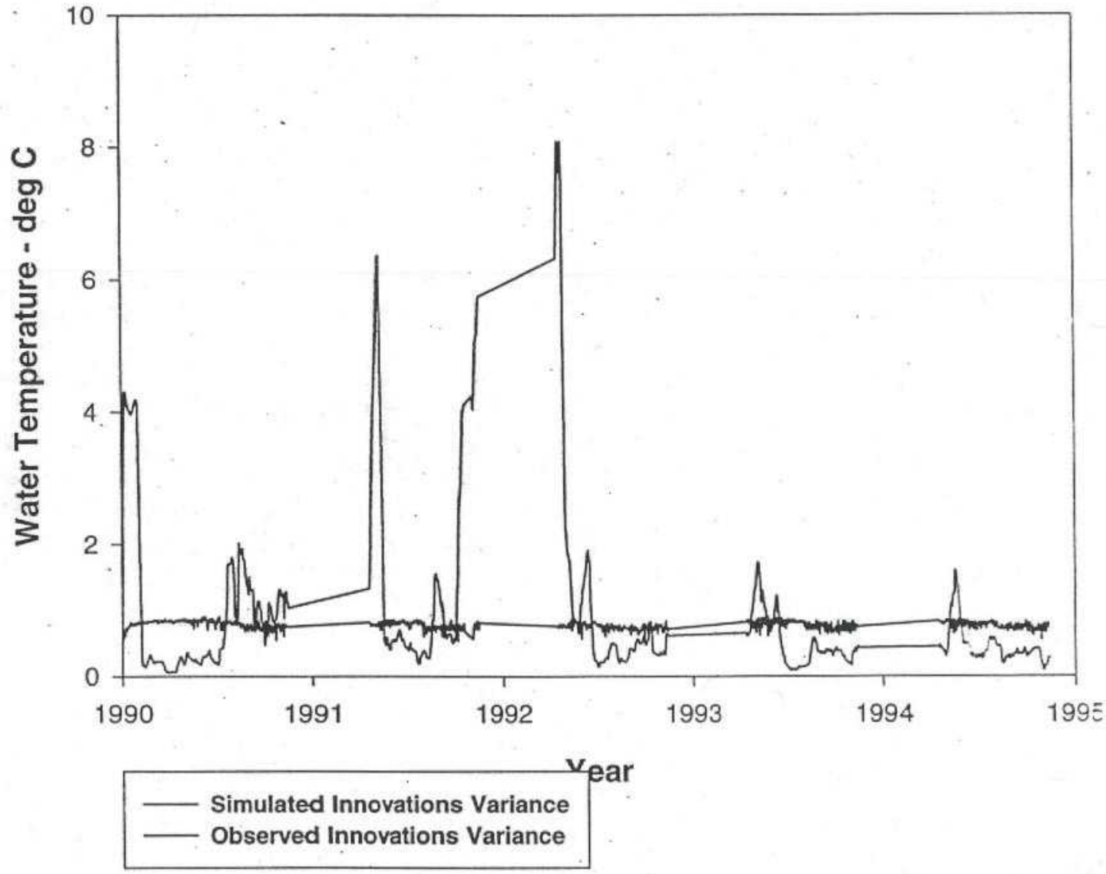


Figure 27. Actual and simulated innovations variance at Ice Harbor Dam for the period 1990-1995.

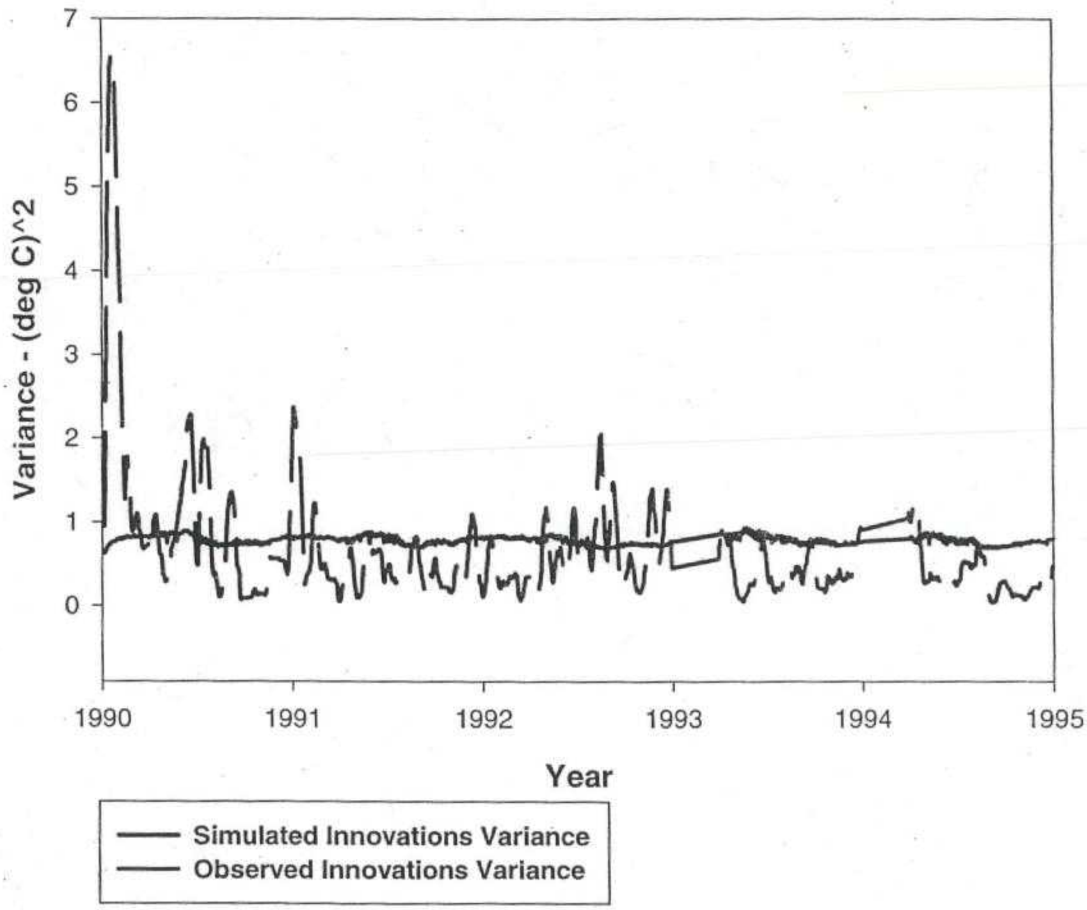


Figure 28. Actual and simulated innovations variance at Lower Monumental Dam for the period 1990-1995.

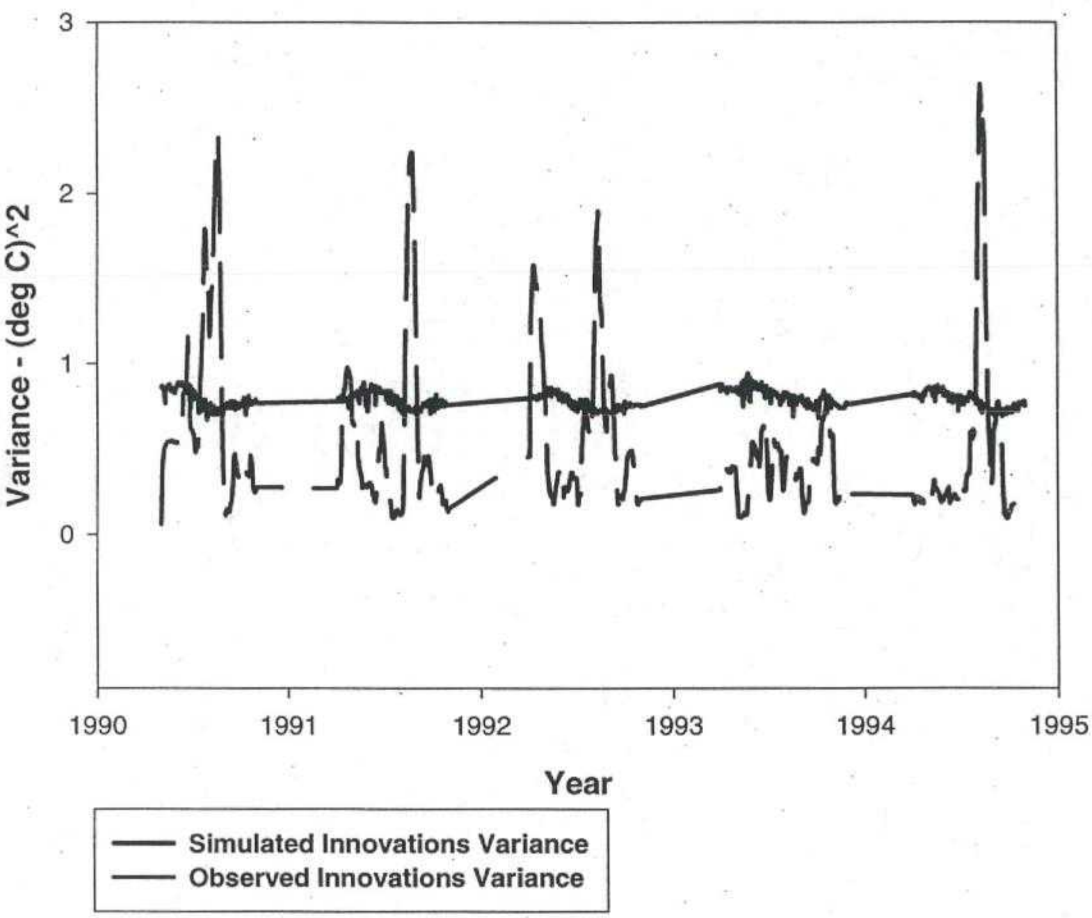


Figure 29. Actual and simulated innovations variance at Lower Granite Dam for the period 1990-1995.

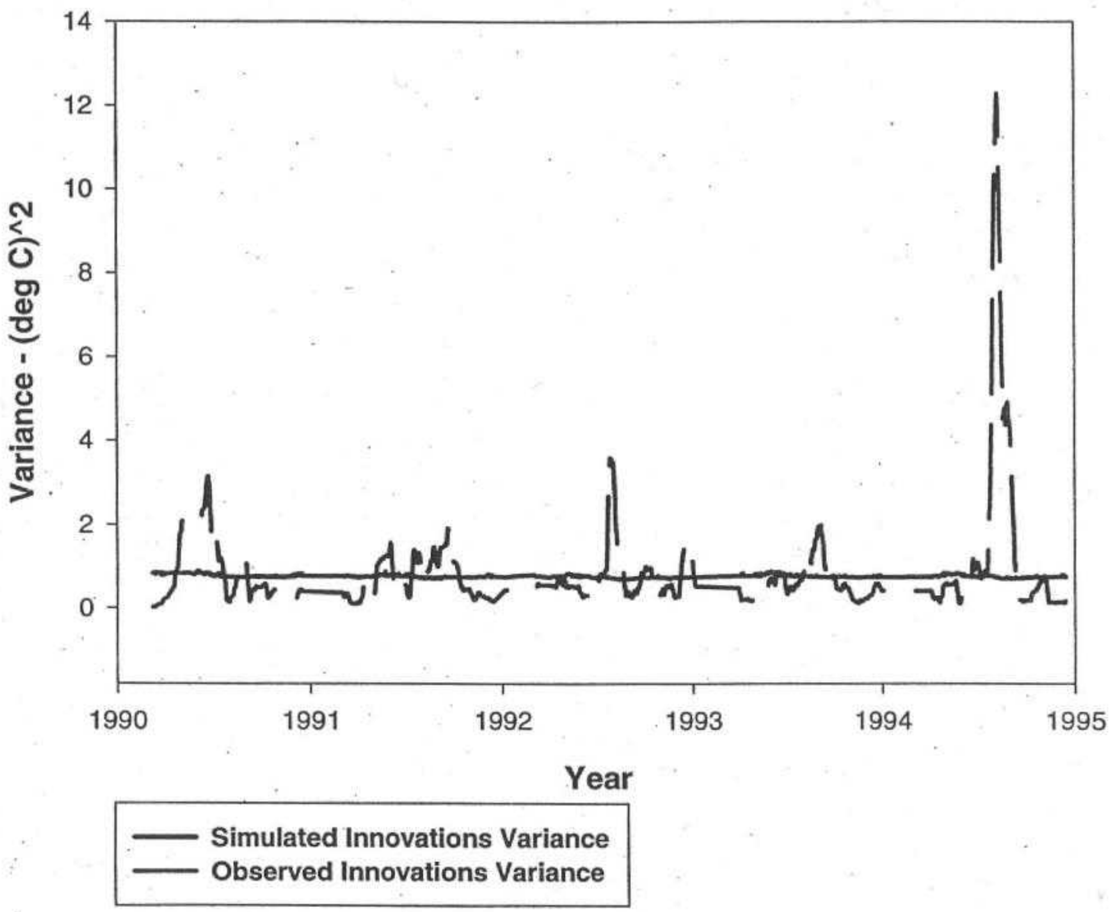


Figure 30. Estimated frequency with which water temperatures exceed 20 deg C in the Snake River with dams in place and existing management

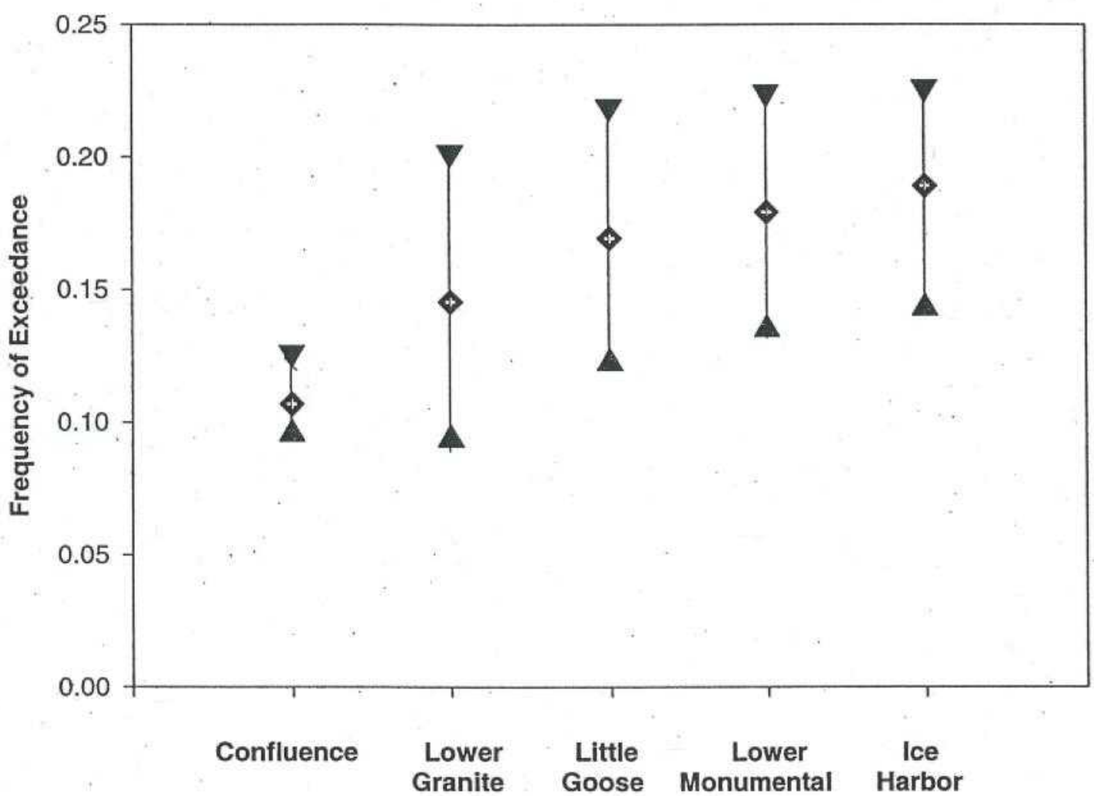


Figure 31. Estimated frequency with which water temperatures exceed 20 deg C in the Snake River with dams removed and existing management

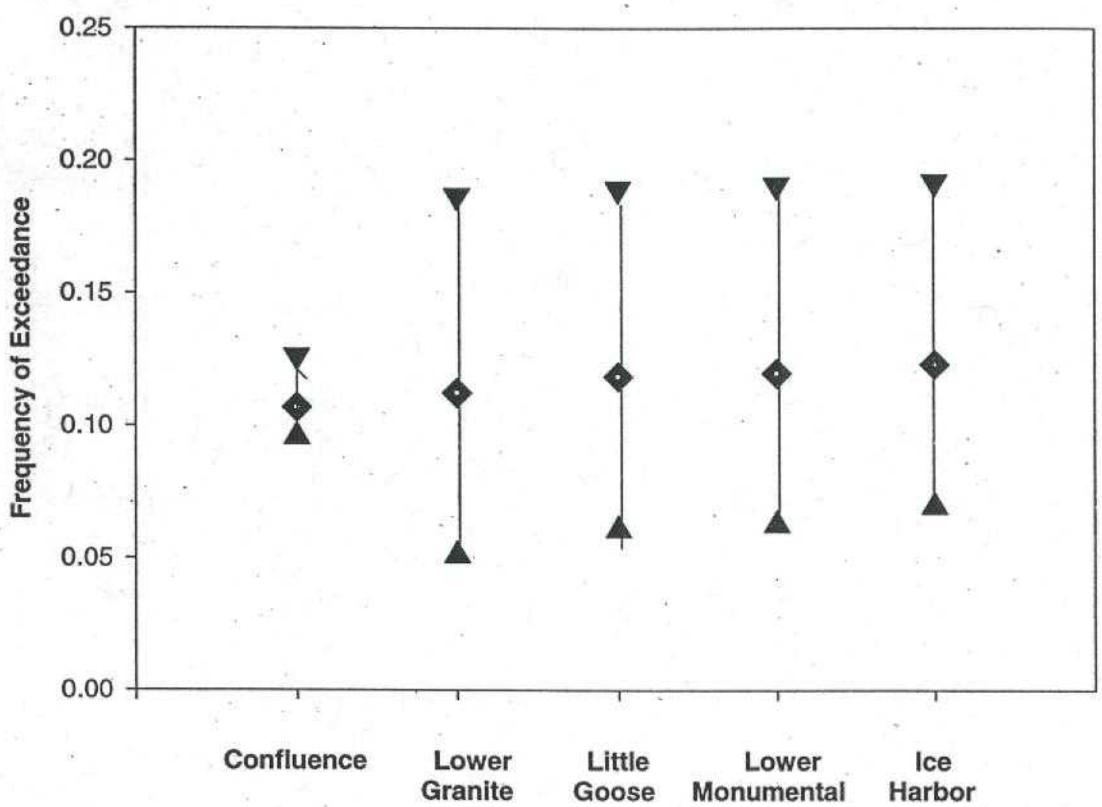


Figure 32. Estimated frequency with which water temperatures exceed 20 deg C in the Snake River with dams in place, tributary temperatures equal to or less than 16 deg C and existing management

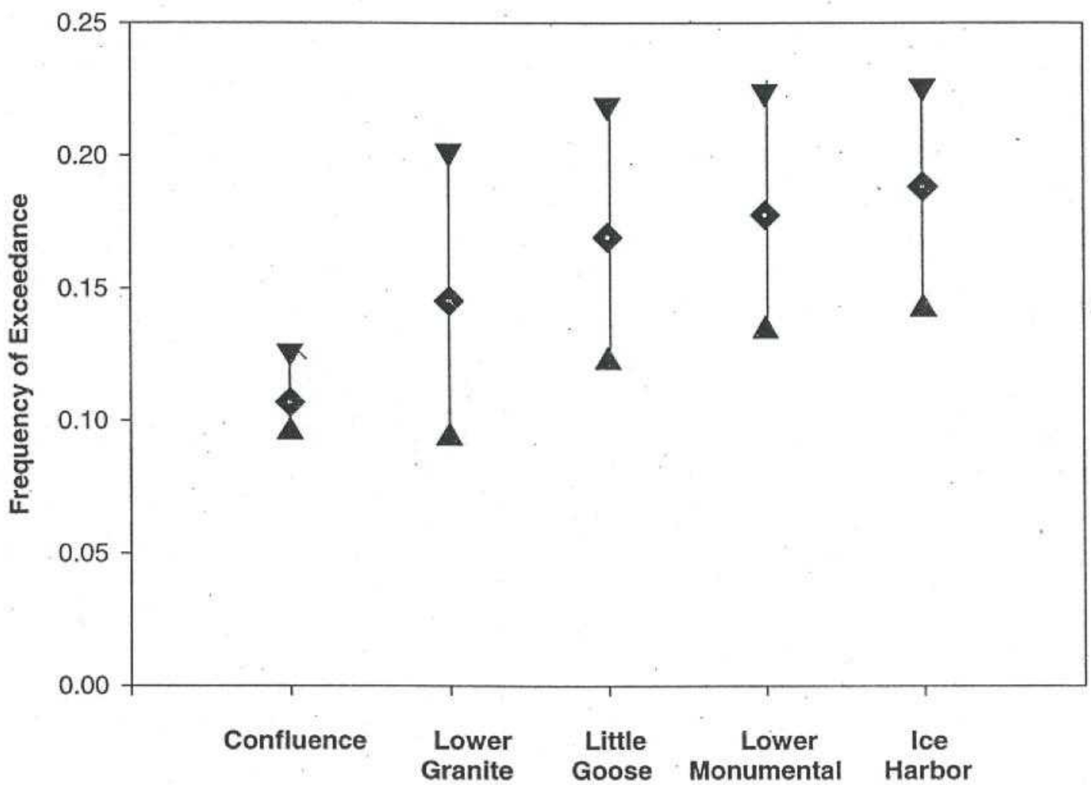


Figure 33. Estimated frequency with which water temperature exceeds 20 deg C in the Columbia River with dams in place and with existing management

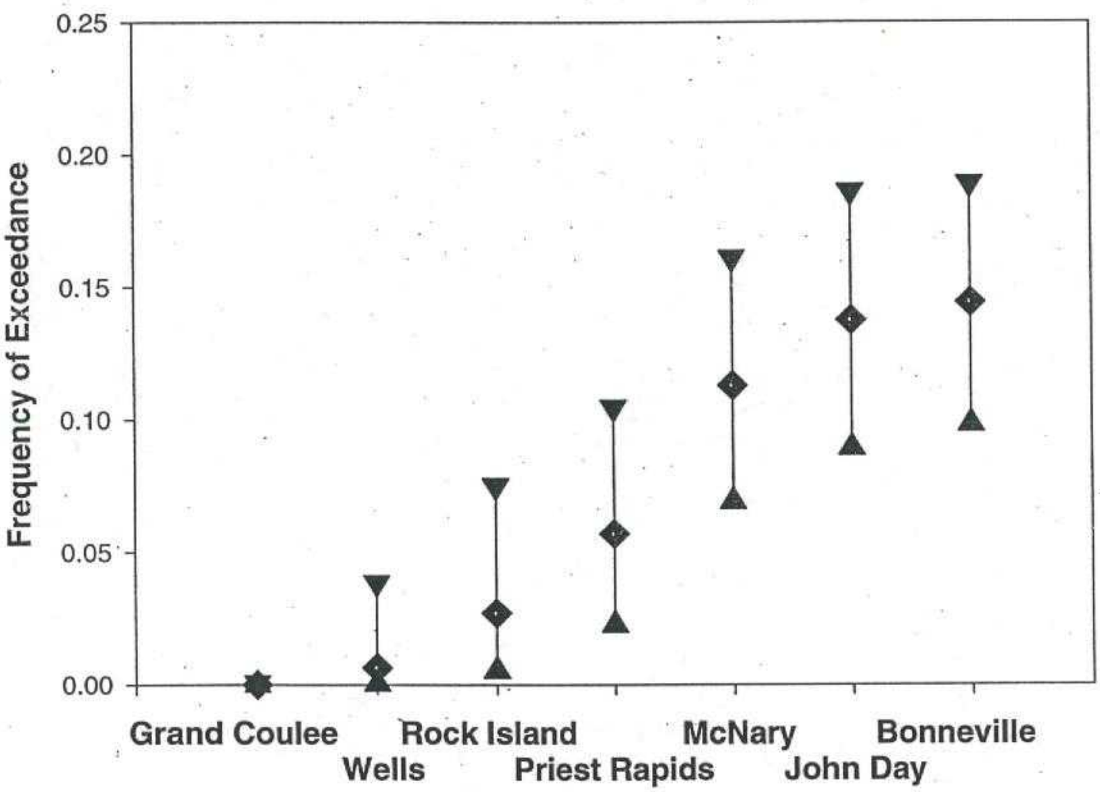


Figure 34. Estimated frequency with which water temperature exceeds 20 deg C in the Columbia River with dams removed and with existing management

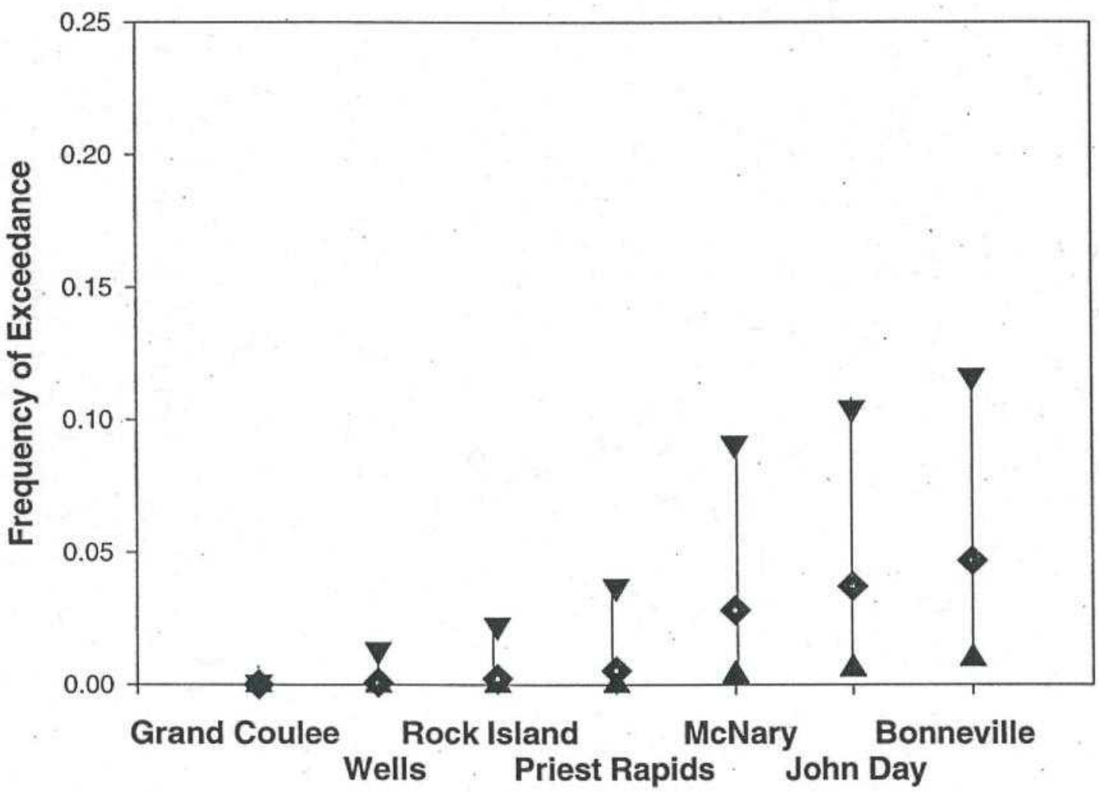


Figure 35. Estimated frequency with which water temperature exceeds 20 deg C in the Columbia River with dams in place, tributary temperatures equal to or less than 16 deg C and with existing management

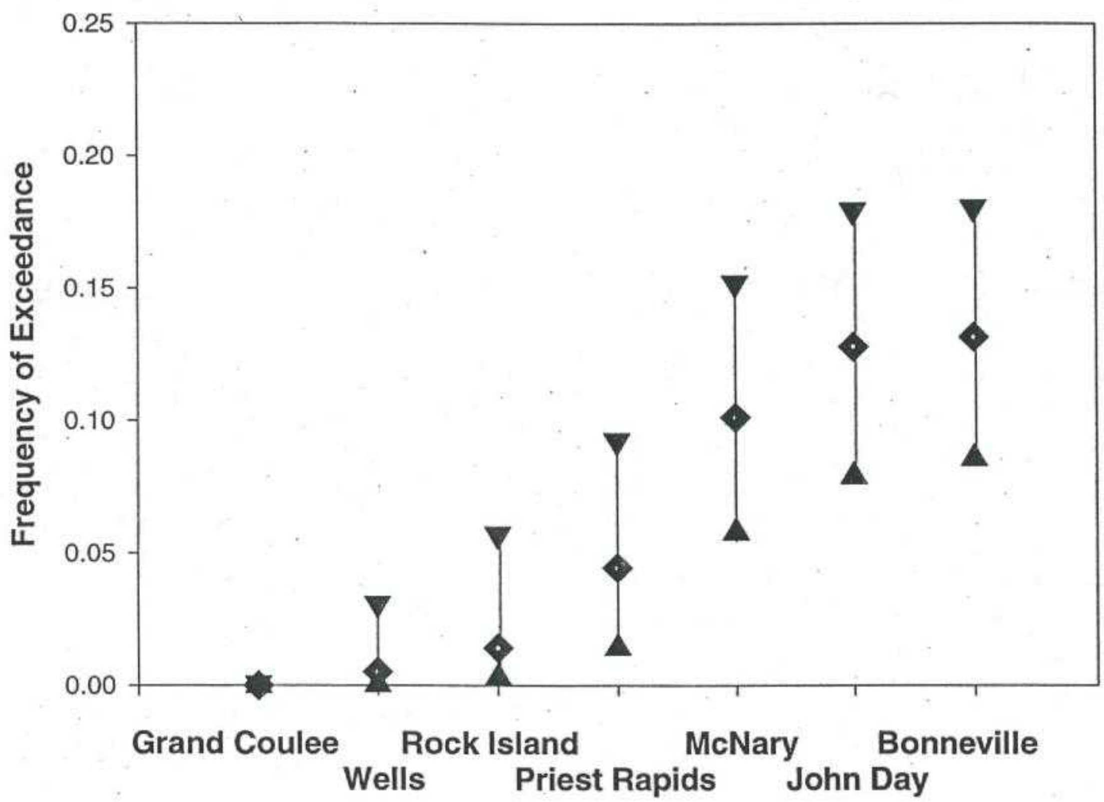


Figure 36. Estimated magnitude with which water temperatures exceed 20 deg C in the Snake River with dams in place and existing management

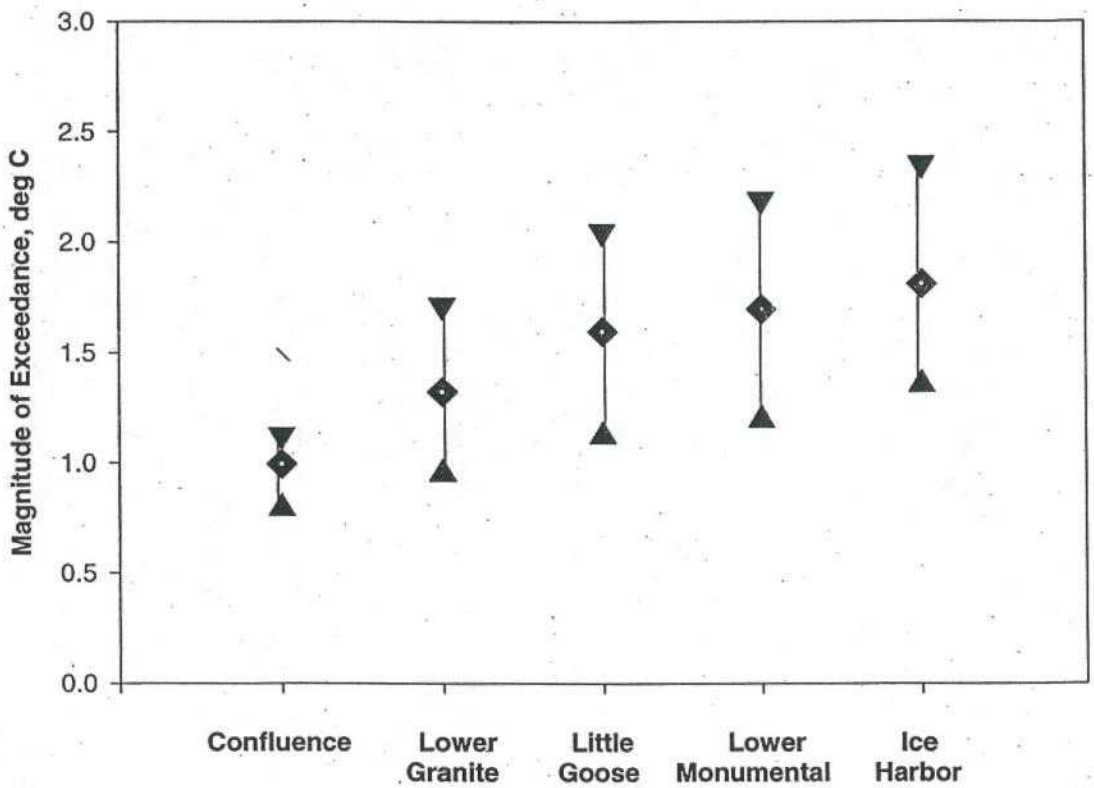


Figure 37. Estimated magnitude with which water temperatures exceed 20 deg C in the Snake River with dams removed and existing management

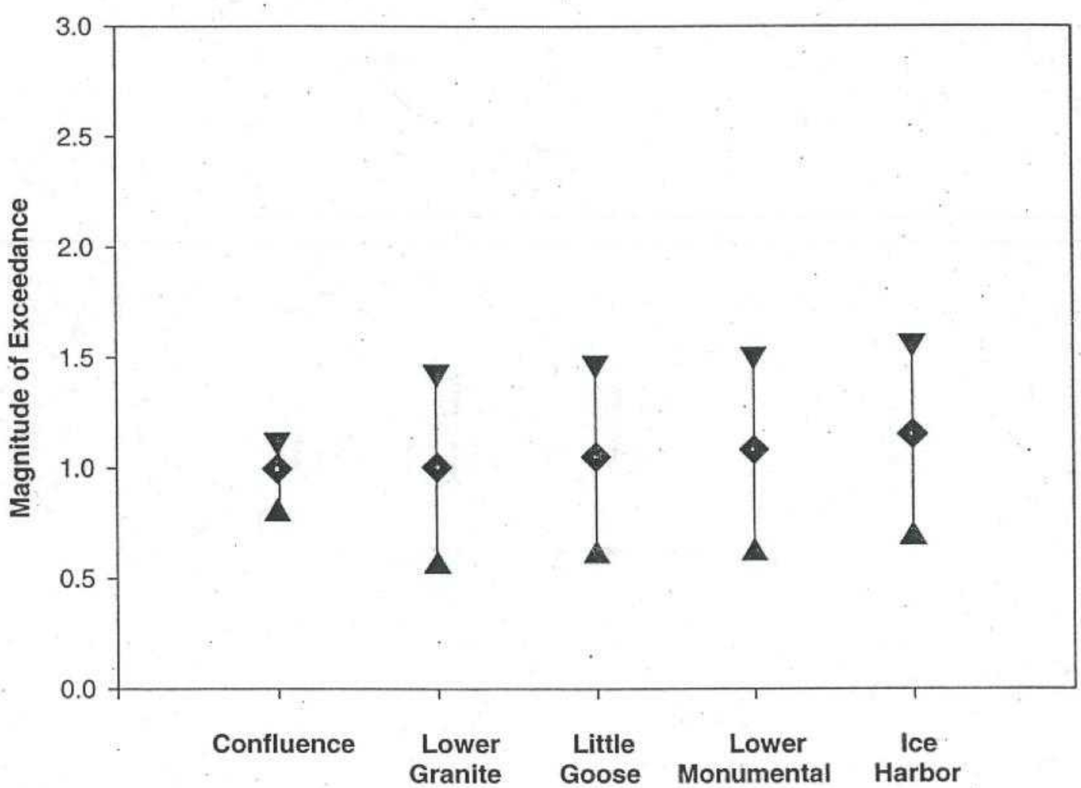


Figure 38. Estimated magnitude with which water temperatures exceed 20 deg C in the Snake River with dams in place, tributary temperatures equal to or less than 16 deg C and existing management

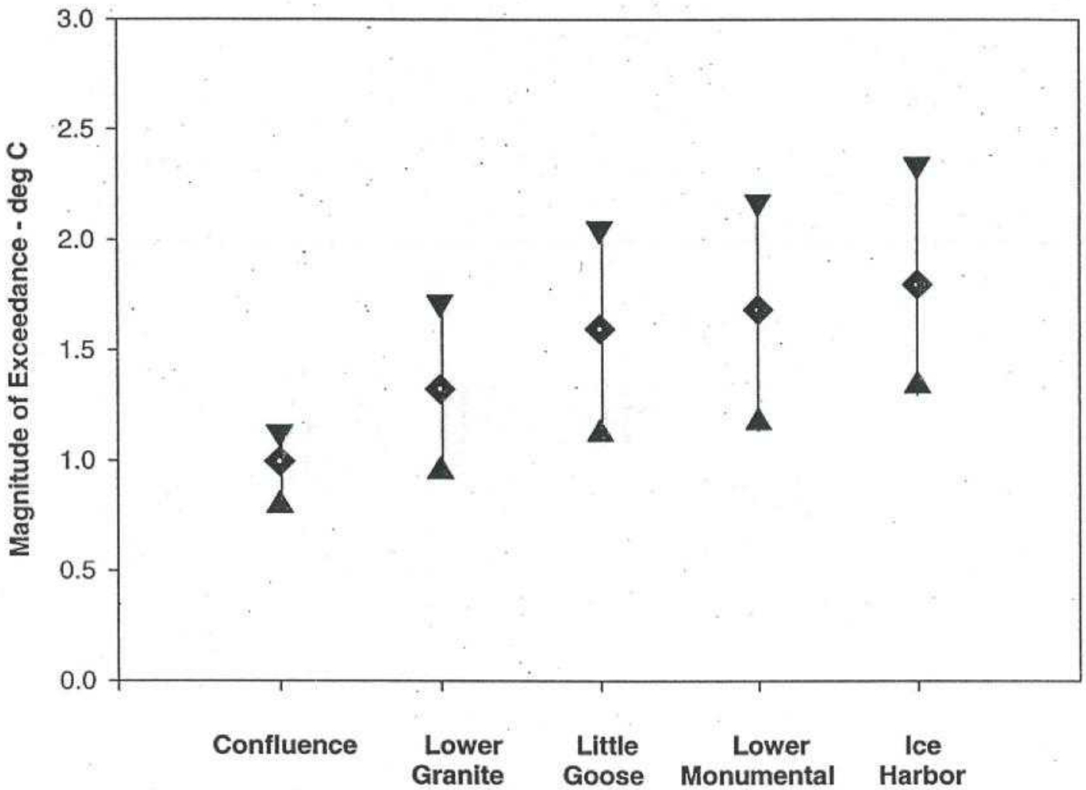


Figure 39. Estimated magnitude with which water temperature exceeds 20 deg C in the Columbia River with dams in place and with existing management

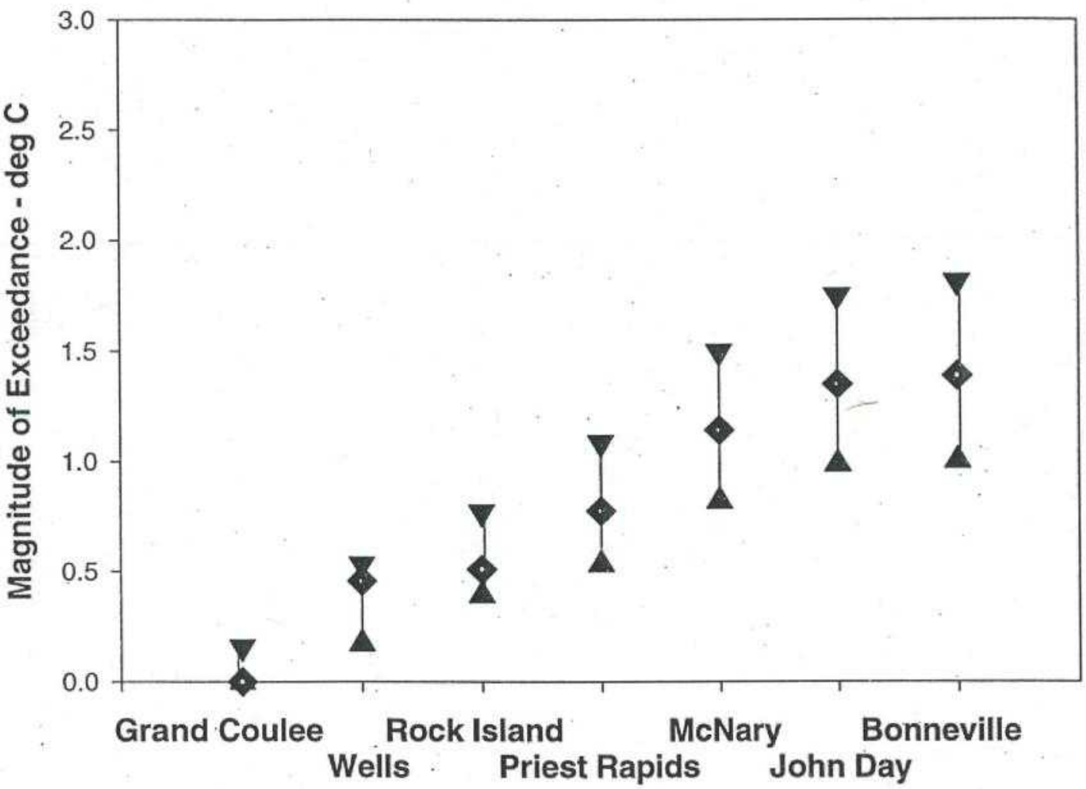


Figure 40. Estimated magnitude with which water temperature exceeds 20 deg C in the Columbia River with dams removed and with existing management

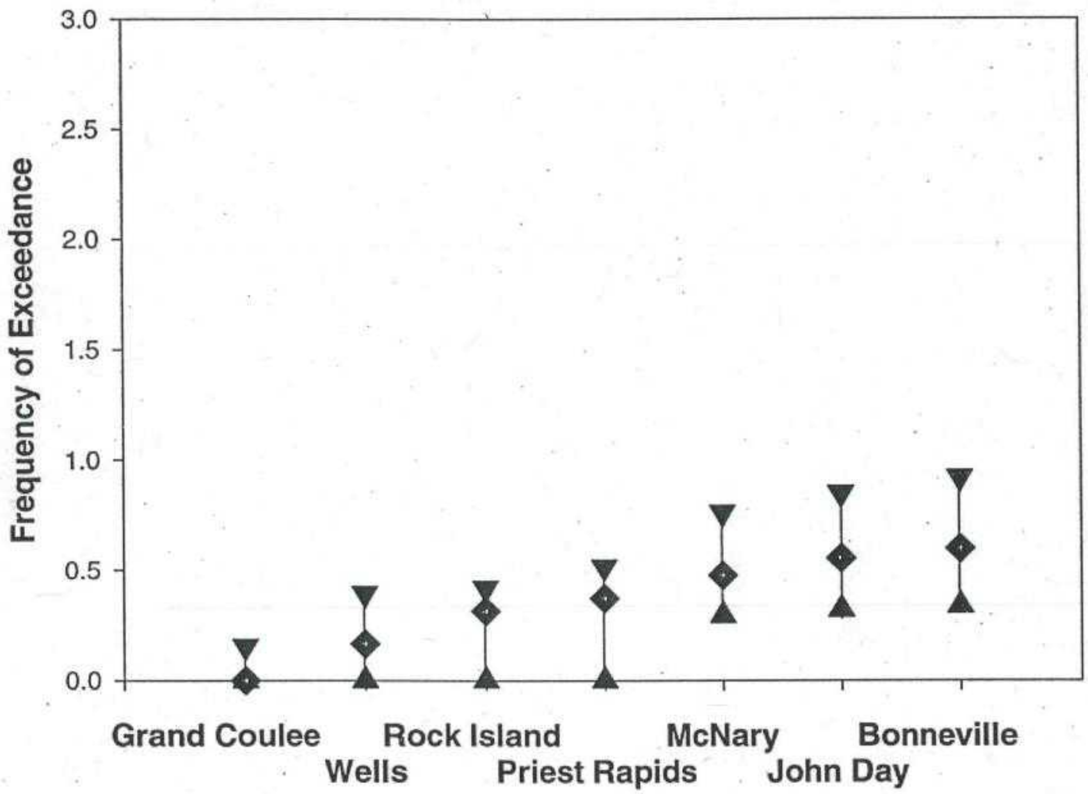
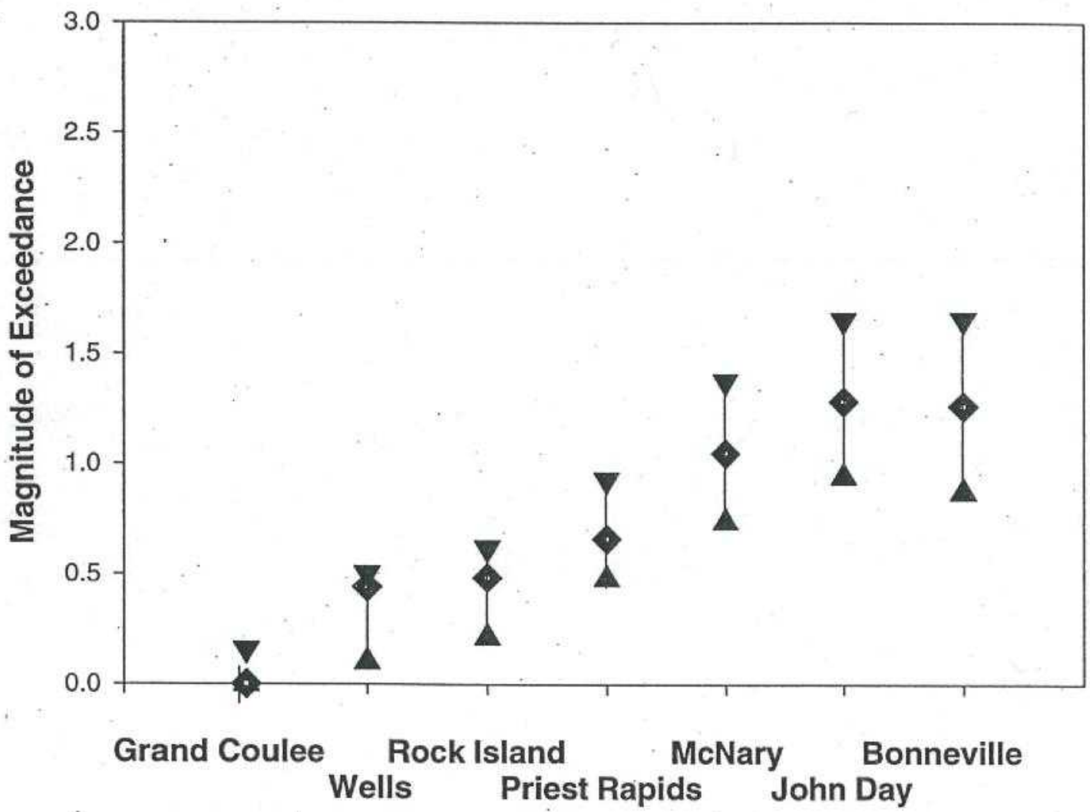


Figure 41. Estimated magnitude with which water temperature exceeds 20 deg C in the Columbia River with dams in place, tributary temperatures equal to or less than 16 deg C and with existing management



APPENDIX A

GEOMETRIC AND HYDRAULIC PROPERTIES

OF THE

COLUMBIA AND SNAKE RIVERS

WITH DAMS IN PLACE

AND

WITH DAMS REMOVED

Table A-1. Surface elevation, volume and surface area of run-of-the-river reservoir segments in the Snake River from Lewiston, Idaho to Ice Harbor Dam.

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	Volume (acre-feet)	Area (acres)
140.0	137.3	746	20825.0	597
137.3	134.6	746	20825.0	597
134.6	131.9	746	20825.0	597
131.9	129.2	746	20825.0	597
129.2	126.5	746	20825.0	597
126.5	123.8	746	35044.0	558
123.8	121.1	746	35044.0	558
121.1	118.4	746	35044.0	558
118.4	116.3	746	38586.0	524
116.3	114.3	746	38586.0	524
114.3	112.3	746	38586.0	524
112.3	110.1	746	57027.0	718
110.1	107.9	746	57027.0	718
107.9	104.5	646	20883.2	580
104.5	101.0	646	20883.2	580
101.0	97.6	646	20883.2	580
97.6	94.1	646	20883.2	580
94.1	90.7	646	20883.2	580
90.7	87.4	646	50635.0	905
87.4	84.0	646	50635.0	905
84.0	81.5	646	56622.0	814
81.5	78.9	646	56622.0	814
78.9	76.6	646	55658.0	727
76.6	74.2	646	55658.0	728
74.2	70.8	646	75002.0	956
70.8	67.5	548	25614.6	518
67.5	64.2	548	25614.6	518
64.2	60.9	548	25614.6	518
60.9	57.6	548	25614.6	518
57.6	54.2	548	25614.6	518
54.2	50.7	548	51914.0	717
50.7	47.1	548	53397.0	738
47.1	44.6	548	57812.0	735
44.6	42.0	548	60125.0	764
42.0	38.3	446	25571.6	752
38.3	34.7	446	25571.6	752
34.7	31.0	446	25571.6	752
31.0	27.4	446	25571.6	752
27.4	23.7	446	25571.6	752
23.7	21.1	446	44783.3	772
21.1	18.5	446	44783.3	772
18.5	16.0	446	44783.3	772
16.0	13.9	446	40202.7	574
13.9	11.8	446	40202.7	574
11.8	9.7	446	40202.7	574

Table A-2. Surface elevation, volume and surface area of run-of-the-river reservoir segments on the Columbia River between Grand Coulee Dam and Bonneville Dam

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	Volume (acre-feet)	Area (acres)
590.0	584.9	978	46717.0	734
584.9	579.9	978	46717.0	734
579.9	574.8	978	46717.0	734
574.8	569.8	978	46717.0	734
569.8	564.7	978	46717.0	734
564.7	559.7	978	46717.0	734
559.7	554.8	978	91643.0	459
554.8	549.9	978	91643.0	459
549.9	545.1	978	91643.0	459
545.1	539.2	803	33809.6	1571
539.2	533.3	803	33809.6	1571
533.3	527.4	803	33809.6	1571
527.4	521.5	803	33809.6	1571
521.5	515.6	803	33809.6	1571
515.6	505.1	719	52658.0	1731
505.1	494.7	719	52658.0	1731
494.7	484.3	719	52658.0	1731
484.3	480.8	719	52604.0	1092
480.8	477.3	719	52604.0	1092
477.3	473.7	719	52604.0	1092
473.7	466.9	619	42688.0	997
466.9	460.1	619	42688.0	997
460.1	453.4	619	42688.0	997
453.4	424.2	580	173964.0	7728
424.2	415.8	580	157110.0	5094
415.8	397.1	491	184014.0	7014
324.0	314.4	357	217147.0	9724
314.4	301.1	357	209010.0	5176
301.1	292.0	357	250113.0	4323
292.0	273.3	276	206635.0	8712
273.3	265.0	276	227752.0	9325
265.0	256.6	276	235460.0	5771
256.6	249.1	276	214530.0	4184
249.1	243.7	276	213204.0	3533
243.7	236.3	276	241671.0	3348
236.3	229.1	276	292632.0	3711
229.1	222.3	276	295188.0	4068
222.3	215.6	276	286356.0	3175
215.6	191.5	182	299532.0	8567
191.5	165.7	82	284148.0	8387
165.7	145.5	82	285538.0	9072

Table A-3. Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Hanford Reach of the Columbia River.

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
397.1	392.4	450	16.0994	0.6010	99.5337	0.2170
392.4	386.7	450	10.4826	0.6491	46.1598	0.2990
386.7	382.1	450	5.1545	0.6966	10.8665	0.3940
382.1	377.4	450	35.6628	0.5364	798.8506	0.0730
377.4	371.6	450	21.0634	0.6032	292.7820	0.1990
371.6	364.4	450	29.5736	0.5646	374.7002	0.1290
364.4	358.3	450	16.1049	0.6030	91.6599	0.2060
358.3	353.6	450	14.0921	0.6336	82.1749	0.2670
353.6	346.3	450	41.4013	0.5346	940.1158	0.0690
346.3	339.5	450	1.4800	0.8018	1.0554	0.6050
339.5	333.6	450	60.2303	0.5596	664.3698	0.1190
333.6	329.4	450	26.2448	0.6340	129.2020	0.2680
329.4	324.0	450	94.4921	0.5597	1585.1760	0.1190

Table A-4. Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Snake River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
139.3	135.1	727	1.3734	0.8395	1219.8387	0.0527
135.1	130.0	714	0.2497	0.9333	46.2064	0.2693
130.0	124.9	700	4.5948	0.6862	33.9653	0.268
124.9	120.5	683	13.1143	0.6076	183.1265	0.1204
120.5	114.9	675	65.4102	0.4679	31.1958	0.2663
114.9	111.2	657	0.4202	0.8997	27.1063	0.3282
111.2	105.0	650	86.6362	0.4700	495.2805	0.0575
105.0	100.0	634	3.6130	0.7320	20.2729	0.3588
100.0	95.0	616	0.4122	0.8931	153.2817	0.1676
95.0	90.0	604	33.1126	0.5367	482.9053	0.0617
90.0	85.0	591	11.5359	0.6274	411.3987	0.0815
85.0	80.0	578	15.8938	0.6009	546.5048	0.0624
80.0	75.0	564	2.8035	0.7458	949.4666	0.0317
75.0	70.0	550	0.0371	1.0999	21.1241	0.3705
70.0	65.0	536	34.9564	0.5409	41.3614	0.2837
65.0	64.1	519	13.6486	0.6047	262.7923	0.1151
64.1	60.0	519	13.6486	0.6047	262.7923	0.1151
60.0	55.0	497	2.8014	0.7103	1.7944	0.5102
55.0	50.0	484	12.9094	0.6103	274.3042	0.1084
50.0	45.2	470	5.7302	0.6849	625.4147	0.0585
45.2	39.6	456	11.7427	0.6265	675.5304	0.0599
39.6	34.7	440	0.8356	0.8345	674.6927	0.0508
34.7	29.7	426	12.8951	0.6176	561.4941	0.0676
29.7	24.9	413	10.0577	0.6458	215.5004	0.1681
24.9	20.5	401	99.3539	0.4457	144.4178	0.1517
20.5	15.0	389	1336.7927	0.2308	217.4554	0.0779
15.0	10.1	371	7.3970	0.6552	528.2647	0.0806
10.1	5.1	356	14.7118	0.6003	738.0669	0.0397
5.1	0.0	344	3.1882	0.7395	236.7204	0.1704

Table A-5. Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Columbia River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
596.1	593.3	1000	2.6338	0.7352	18.0219	0.3374
593.0	590.0	980	2.6338	0.7352	18.0219	0.3374
590.0	582.3	957	0.7270	0.8120	71.3679	0.223
582.3	574.6	950	8.0662	0.6987	1099.0507	0.0508
574.6	568.0	942	0.7307	0.8405	33.2019	0.2845
568.0	560.5	931	3.0785	0.7268	41.2264	0.2468
560.5	556.1	923	78.9803	0.4911	106.4525	0.1716
556.1	550.5	915	13.6134	0.5940	77.8754	0.1894
550.5	543.5	875	0.9457	0.7627	28.1202	0.2858
543.5	536.0	795	241.4499	0.3980	569.5330	0.045
536.0	528.5	787	3.6436	0.7084	37.3599	0.2799
528.5	524.1	773	3.6436	0.7084	37.3599	0.2799
524.1	521.0	761	4.3695	0.7015	30.4070	0.3061
521.0	516.6	755	21.8397	0.5685	62.3113	0.2475
516.6	513.5	742	8.9346	0.6667	204.5063	0.1391
513.5	509.6	740	8.9346	0.6667	204.5063	0.1391
509.6	504.0	737	50.0570	0.5268	373.5261	0.0727
504.0	496.7	727	0.6773	0.8267	1.3620	0.5177
496.7	489.3	716	30.0809	0.5715	141.8256	0.1773
489.3	481.0	702	2.1101	0.7502	24.0741	0.3206
481.0	474.5	682	4.5249	0.7103	29.2092	0.3209
474.5	472.8	645	18.5590	0.6002	381.3065	0.1018
472.8	465.3	638	18.5590	0.6002	381.3065	0.1018
465.3	461.1	622	98.3723	0.4602	601.2292	0.0486
461.1	456.9	596	98.3723	0.4602	601.2292	0.0486
456.9	452.1	591	46.2149	0.4941	52.8461	0.1974
452.1	447.2	550	19.1734	0.5999	97.9604	0.2138
447.2	441.3	541	9.3458	0.6566	249.7985	0.1548
441.3	435.8	533	34.7602	0.5667	650.6808	0.087
435.8	427.5	529	177.3813	0.4614	1239.7894	0.0537
427.5	419.2	523	116.7612	0.5084	2121.0964	0.0471
419.2	415.0	514	116.7612	0.5084	2121.0964	0.0471
415.0	412.2	490	304.7172	0.3970	481.3450	0.1025
412.2	409.5	472	304.7172	0.3970	481.3450	0.1025
409.5	407.1	468	71.4189	0.5197	589.8682	0.1286
407.1	403.1	459	71.4189	0.5197	589.8682	0.1286
403.1	397.3	454	93.4202	0.5409	434.8807	0.1681
397.1	392.4	450	16.0994	0.6010	99.5337	0.2172
392.4	386.7	450	10.4826	0.6491	46.1598	0.299
386.7	382.1	450	5.1545	0.6966	10.8665	0.3948
382.1	377.4	450	35.6628	0.5364	798.8506	0.0731
377.4	371.6	450	21.0634	0.6032	292.7820	0.1991
371.6	364.4	450	29.5736	0.5646	374.7002	0.1297
364.4	358.3	450	16.1049	0.6030	91.6599	0.2066
358.3	353.6	450	14.0921	0.6336	82.1749	0.2678

Table A-5 (continued). Surface elevation and parameters for equations 14 and 15 describing the hydraulics of the Columbia River with dams removed

Beginning River Mile	Ending River Mile	Elevation (feet abv MSL)	A_a	B_a	A_w	B_w
353.6	346.3	450	41.4013	0.5346	940.1158	0.0693
346.3	339.5	450	1.4800	0.8018	1.0554	0.605
339.5	333.6	450	60.2303	0.5596	664.3698	0.1195
333.6	329.4	450	26.2448	0.6340	129.2020	0.2683
329.4	324.0	450	94.4921	0.5597	1585.1760	0.1194
324.0	319.0	319	8.1919	0.6777	15.5388	0.4047
319.0	315.0	319	8.1919	0.6777	15.5388	0.4047
315.0	310.0	311	8.1919	0.6777	15.5388	0.4047
310.0	305.0	304	3.6979	0.7577	4.8827	0.5124
305.0	300.0	298	0.1471	0.9998	50.1033	0.3363
300.0	295.0	290	0.3042	0.9383	32.7658	0.3662
295.0	290.0	279	5.5772	0.7054	16.3420	0.4116
290.0	285.0	267	7.3793	0.6946	20.1463	0.3881
285.0	280.0	260	1.2465	0.8363	184.3870	0.2182
280.0	275.0	256	222.7504	0.4407	2.3317	0.5328
275.0	270.0	244	1.0377	0.8121	0.6808	0.6399
270.0	265.0	237	0.2465	0.9716	7.7394	0.5002
265.0	260.0	230	12.4667	0.6535	161.5547	0.2115
260.0	255.0	224	0.2303	0.9490	21.5631	0.3816
255.0	250.0	221	22.1718	0.6173	88.7304	0.2695
250.0	245.0	216	10.2468	0.6940	178.6500	0.2291
245.0	240.0	212	0.0527	1.0805	19.4272	0.3972
240.0	235.0	209	12.0935	0.6696	71.3909	0.2919
235.0	230.0	206	524.6108	0.3843	935.8895	0.07
230.0	225.0	199	1.6655	0.7684	476.1715	0.1207
225.0	220.0	181	3.5737	0.7293	260.5219	0.1704
220.0	215.0	176	1878.4895	0.2832	1367.9987	0.0409
215.0	210.0	164	7.9771	0.6813	141.3714	0.2097
210.0	205.0	160	27.2777	0.5970	634.6995	0.105
205.0	200.0	148	41.1050	0.5813	9.0817	0.4604
200.0	195.0	140	41.1050	0.5813	9.0817	0.4604
195.0	190.0	137	2244.5522	0.2914	680.3396	0.095
190.0	185.0	76	0.9950	0.8306	58.5292	0.2722
185.0	180.0	75	5.2198	0.7354	745.1066	0.0994
180.0	175.0	73	1800.4440	0.3021	106.4071	0.2303
175.0	170.0	72	227.3922	0.4594	121.2100	0.2483
170.0	165.0	69	27.8419	0.6190	574.8106	0.1414
165.0	160.0	65	21.0582	0.6312	959.7112	0.1039
160.0	155.0	62	21.0582	0.6312	959.7112	0.1039
155.0	150.0	59	2.7886	0.7433	302.9572	0.1456
150.0	146.1	48	2.7886	0.7433	302.9572	0.1456
146.1	140.0	24	0.3407	0.8362	1.1586	0.5184